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by

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METALS JOINING IN THE DEEP OCEAN

by

Arnold P. Moore

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ABSTRACT

The objective of this thesis is twofold: to conduct a systems study of those factors which must be considered in developing a capacity to join metals in a deep marine environment and to present the development and design of an underwater welding device which may prove useful in certain deep ocean applications.

Factors which are considered in the first part of this paper include present and projected needs for metals joining in the deep sea, technical problems inherent in deeper operation and the dependency of potential processes on diving system capability. In the examination of these topics, processes which appear to be most promising for practical application are identified and technical and diving related problems worthy of more detailed study are pinpointed. Economic factors are considered whenever possible.

The design related phase of this paper presents the experimental and analytical development of an underwater stud welding process and the conceptual design of a remotely operated deep ocean joining system employing this process.

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Title: Professor of Ocean Engineering and Materials Science

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TABLE OF CONTENTS

PART TWO CONCEPTUAL DESIGN

LIST OF FIGURES

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LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Objectives and Approach

The rapid expansion of ocean based industries, most notably the offshore petroleum industry, has highlighted the need for reliable, high quality, underwater joining processes. Prior to the late 1960's little economic motivation to fund development of these processes existed and, as a result, underwater welds were of such low quality that their uses were largely limited to salvage work and emergency repair. Developmental efforts underway since that time, however, have produced several fully operational techniques capable of producing sound welds in relatively shallow water. A combination of diving system limitations, pressure-related technical problems and a general lack of need have, until very recently, restricted the use of these techniques to depths of 200 feet or less. A number of papers dealing with these efforts and with fundamental research on underwater welding have been produced, but there is little literature dealing specifically with the problems of metals joining at more extended ocean depths.

The objective of this study is to examine those factors which must be considered in developing a capacity to join metals in a deep marine environment. These factors include the present and projected needs for metals joining in the deep sea, technical problems associated primarily with the effects of pressure and the dependency of potential processes on diving system capability.

Before turning to these individual factors, it is necessary to

gain an understanding of the manner in which they interact. Figure 1-1 illustrates the steps in the development of a new joining process for the deep ocean. First, a need is recognized which can be met fully or partially by the employment of some metals joining process. The next two steps are interdependent and must be undertaken concurrently. The process most suitable for meeting the requirement must be identified and any technical problems associated with working at the intended depth must be solved. At the same time, a diving system must be selected which is capable of delivering and employing the joining process. In a complete underwater repair or fabrication system, additional elements may also be selected and worked into the design.

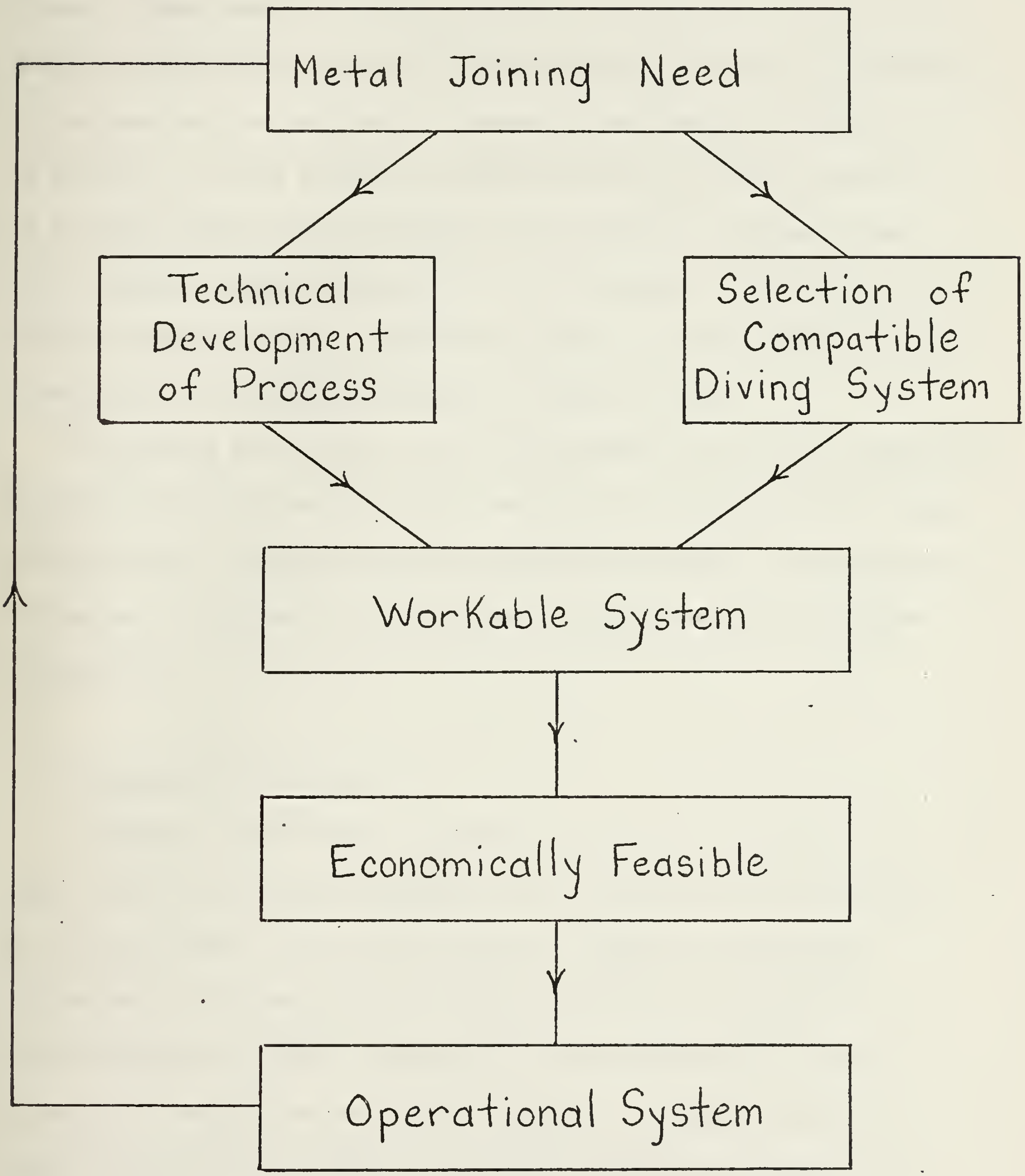
After the joining process and the diving system have been integrated into a workable overall system, two possible tests of economic feasibility should be considered. Is the final operational system able to complete its intended task more cheaply than any existing system? Is the system's cost justified by the economic return expected as a result of its employment? Both developmental and operating costs of the proposed system must be considered.

In Figure 1-1, the loop leading back from the operational system block to the need block indicates that the development of a workable system where none previously existed often leads to the identification of similar needs. These, in turn, may lead to the requirement to develop other new systems.

In completing this thesis, a two step procedure will be followed. In the first part, a systems study of the total problem of joining

Figure 1-1

Development of a Deep Ocean Joining System



metals in the deep ocean will be conducted. Chapter 2 commences this study by examining present and future needs. In this chapter, industries and governmental agencies with urgent needs are identified, present trends toward fulfilling joining requirements are traced and those processes which appear to have potential for practical employment in the deep sea are outlined. Chapters 3 and 4 build on Chapter 2. In Chapter 3, diving system limitations which affect the operation of processes identified in Chapter 2 are studied. Chapter 4 deals with technical problems expected in the employment of these same processes at greater depths. Information useful in determining economic feasibility is presented in Chapters 2 and 3 as well.

The second part of this thesis compliments the first by conducting a feasibility study and conceptual design of an integrated deep ocean joining system, employing a newly proposed underwater joining process. In Chapter 6, this will be undertaken following the steps outlined in Figure 1-1.

1.2 Background Information

Underwater fabrication techniques are not new. As early as 1927, the U.S. Navy used underwater flame cutting for salvage work.[45] By the late 1940's, arc welding could be conducted successfully underwater in all positions.[30] However, traditional underwater shielded metal arc (SMA) techniques produce welds with a tensile strength of only 80 percent of air welds and a notch toughness of only 50 percent.[62] As a result, underwater welding was avoided for a

number of years except in certain applications. These included salvage and temporary repair, where limitations were offset by special needs of short duration, and a few non-critical underwater tasks such as attaching anodes to ship hulls.

In the later half of the 1960's, research efforts in the United States were begun to develop the joining capabilities demanded by the booming offshore oil industry. These efforts were overdue. In fact, many companies had ceased detailed underwater inspection of their offshore structures because methods to satisfactorily repair any damage found did not exist.[25] This research has resulted in the development of several techniques which have been used successfully a number of times in relatively shallow water. Many papers have been produced describing these techniques in detail, but for the sake of completeness, a brief summary is in order.

Dry welding methods, wherein the joint or area to be welded is surrounded by an evacuated chamber, are in wide use and have given excellent results. There are several variations of dry welding methods. Dry habitat or hyperbaric chambers, enclosing both the diver and the work, are used by several companies and have produced excellent results in underwater pipeline repairs and tie-ins. Both gas metal-arc (GMA) and gas tungsten-arc (GTA) processes have been used within these chambers and both are capable of code quality welds. This type of chamber is an expensive technique and not easily adapted to configurations other than pipelines, but the high quality work it yields justifies its cost in certain pipeline applications.[23] Another type of dry underwater welding has been developed by Sub Ocean

(formerly Hydrotech). Two forms of the basic idea are used. One, the portable dry spot, (PDS) consists of a GMA device enclosed in a small gas filled pressurized chamber which can be manipulated over the joint by a diver-welder. The size of the welding head limits the flexibility of this process as far as joint design is concerned, but commercial applications for this process are increasing.[46] The second Sub Ocean technique, termed the Hydrobox, consists of enclosing the weld joint in a plastic box and evacuating the area with an inert gas. A diver manipulates a GMA welding gun inserted into the box from below. Both techniques are capable of code quality welds.[11]

Wet welds are produced by using an arc directly in the surrounding water. As noted earlier, SMA techniques have been used underwater for more than thirty years. The traditional technique, which gives welds of low tensile strength and notch toughness, consists of dragging the electrode along the workpiece without the welder holding an arc gap. The arc burns in a cavity formed inside the flux covering.[62] Since 1970, however, Chicago Bridge and Iron Company (CBI) has developed a wet multipass technique in which the diver-welder must hold an arc gap. Because of the tempering effect of successive passes on those below, higher quality welds suitable for permanent repairs can be made. In fact, CBI has successfully completed a number of underwater repair tasks on such structures as pilings, docks, pipelines and offshore production platforms. In order to successfully utilize this technique, highly trained diver-welders using specially developed electrodes and other devices must be employed.[25,26,27] Another SMA technique, still under

development, employs a small shroud around the electrode to trap gases generated by the arc in order to form a dry atmosphere around the arc.[55] Arc processes which have not as yet found commercial application include the wet plasma-arc and wet gas metal-arc techniques.[10] Other joining processes now being developed for possible underwater use include explosive welding, exothermic welding, mechanical joining techniques and velocity powered stud guns.

Problems encountered in underwater welding in an actual marine environment may be caused by several factors. Visibility may be poor in the operational area and diver performance may be limited by a lack of stability or extreme cold. However, the most severe problems are created by the surrounding water environment which:[10]

1. produces a severe quenching action, cooling the weldment rapidly and causing a hard and brittle weld.
2. causes the formation of bubbles when exposed to the intense heat of the welding arc, creating porosity problems.
3. dissociates into hydrogen in the presence of the arc, possibly causing hydrogen-induced cracking.

All of the processes described above have received their greatest use in waters less than 200 feet deep. As industrial requirements for operations in deeper waters increase, additional problems will be encountered. Allowable diver "bottom" or working time decreases as depth increases, unless expensive saturation dives are employed. As depth increases farther, practical diving limits are reached and submersible, or remotely controlled, manipulator techniques must be

employed. In addition, increased pressure may have an adverse effect on the behavior of a process. Investigations indicate that pressure certainly has an effect on an electric arc.[7,12,40,48]

A recent test suggests that much greater operating depths may soon be attained. Taylor Diving Company successfully welded a test section of 32 inch diameter pipe at 540 feet in the Gulf of Mexico using a hyperbaric chamber. This test was conducted 200 feet deeper than any previous welding completed in the open sea and was designed to test the company's capability to undertake the welding of tie-ins on a North Sea gas pipeline in 1974-1975.[63]

CHAPTER 2 PRESENT AND PROJECTED NEEDS

The purpose of this chapter is to examine needs for metals joining processes in the deep sea. This will be accomplished by surveying those industries and other interests which either presently operate in the deep ocean or are expected to operate there in the near future. In this manner two objectives can be met. First, processes which appear to be most promising for practical application can be recognized so that technical and diving related problems worthy of more detailed study can be pinpointed. Next, industries or governmental agencies which are the driving forces behind the development of underwater joining processes can be isolated so that incentives which determine the direction of technical development can be examined.

Technology is a product of both incentive and time. The rate of technical development depends on the economic and political incentive to invest the required capital. Incentive, however, can be whetted or dampened by previous technology. As a result a closed cycle is often observed wherein economic needs motivate the development of technology and advancing technology points the way for potential economic gain. The direction of new technology is also determined by previous developments since economic factors generally favor the development of processes which seem to offer the quickest solutions with the least technical risk.

Ocean industries are presently in their infancy. It is difficult to predict future needs from the scant activity now observed in the shallower portions of the world's oceans. However, some idea of

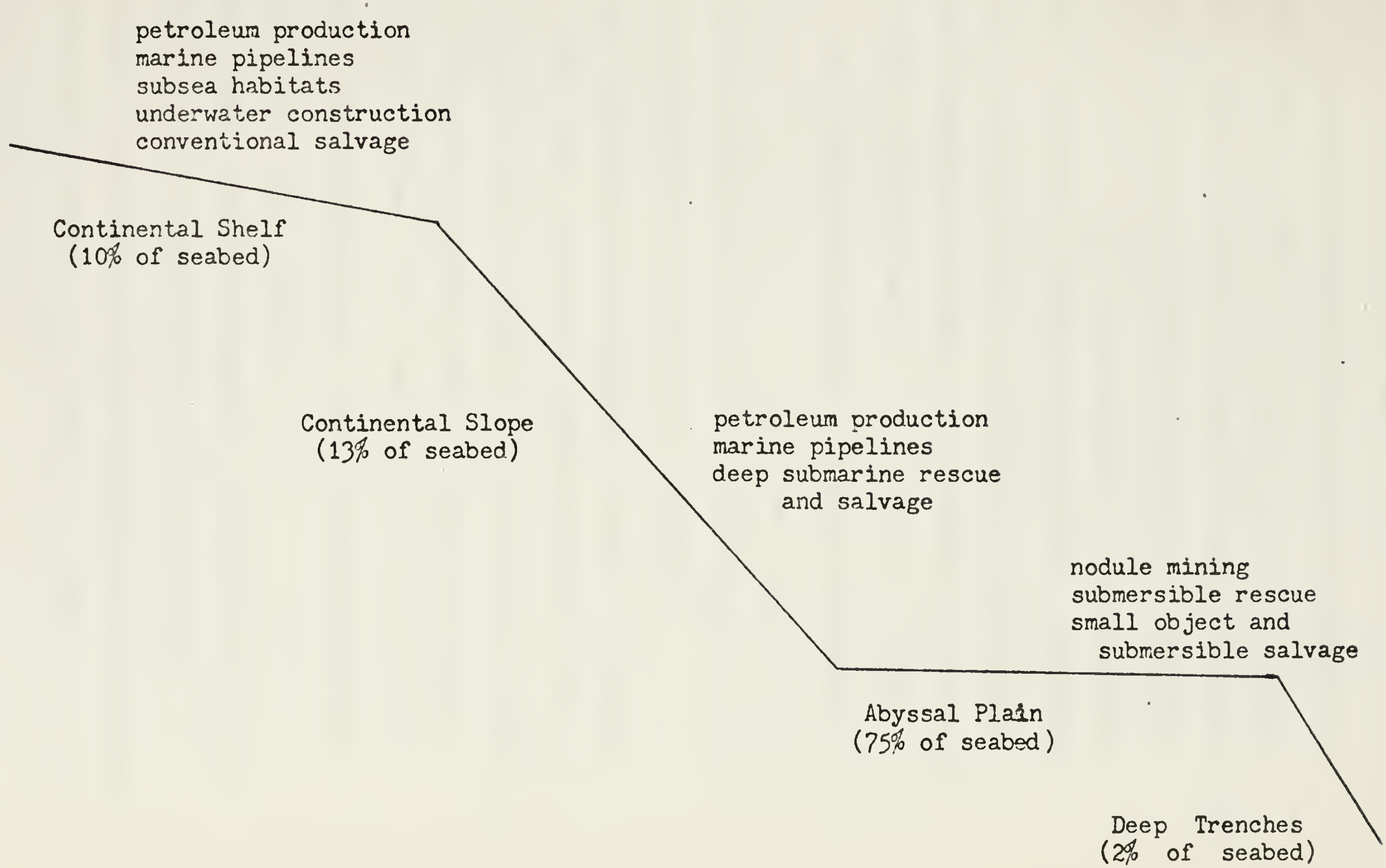
potential technical needs can be gained by examining a profile of the ocean bottom such as that depicted in Figure 2-1. At the present time most, if not all, activities requiring the capability to fabricate metals take place on the continental shelf. As its name implies, the continental shelf, occupying only about ten percent of the seabed, is a gently sloping terrace gradually increasing in depth from the shore to where the sharp incline of the continental slope begins. The dividing line between shelf and slope varies throughout the world, averaging about 400 feet, but angling down to a maximum of 2000 feet in a few areas. The width of the continental shelf ranges from a minimum of less than one mile to a maximum of about 800 miles.[19]

Activity in offshore waters is now moving primarily into the deeper waters of the continental shelf itself. As long as such moves are confined to the shelf, depth requirements for fabrication processes will stretch only a fairly small amount. However, serious activity on the continental slope and beyond is expected to begin very shortly. Seismic petroleum exploration is being actively conducted on the slope and plans are being advanced and equipment tested to conduct mining operations on the abyssal plain. This type of activity means that depth needs for fabrication equipment may increase drastically in a relatively few years.

2.1 Needs of the Offshore Petroleum Industry

The primary economic impetus to extend metals joining technology deeper into the ocean is coming from the offshore petroleum industry.

Figure 2-1 Present and Future Ocean Activity



Petroleum is by far the most important marine resource with approximately 19 percent of the world's current crude oil production coming from subsea deposits.[22] More than 80 nations around the world are engaged in some sort of offshore petroleum activity and proven offshore reserves in the free world total more than 500 billion barrels. The United States Geologic Survey's estimate for deposits off the coast of the United States is from 65 to 130 billion barrels of oil and from 395 to 790 trillion cubic feet of gas. The National Petroleum Council estimates that the area out from shore to a water depth of 200 meters (656 feet) probably contains from 55 to 70 percent of potential reserves; the area between 200 meters and 2500 meters (8200 feet) water depth from 20 to 35 percent; the area between a water depth of 2500 meters and the seaward edge of the continental rise from 1 to 15 percent and the deep ocean seabed only up to 2 percent.[35]

Most actual production offshore comes from waters of less than 200 feet with very little production at depths greater than 400 feet. However, exploratory drilling is going on in water depths in excess of 2,000 feet and Exxon has completed a well in 1,400 feet of water in the Santa Barbara Channel.[2] The trend is clearly to drill and produce in deeper waters when increased costs are justified by the potential return from sizable deposits.

Underwater metals joining techniques are required for the repair of both surface and subsea production sites and in the repair of undersea pipelines.[63] In addition, underwater joining processes may be required in the initial fabrication of pipelines in depths beyond the capability of surface laying barges.[53]

2.1.1 Fixed Platforms

To date, all but a few offshore wells have involved the construction of fixed bottom platforms to serve as drilling or production bases. Fixed platforms have been installed in waters in excess of 400 feet and are being designed for use in water up to 1000 feet in depth.[22] The cost of these structures increases rapidly with depth. In 100 feet of water, the cost of the platform alone exceeds $1.5 million; in 350 feet, $4 million; and in 600 feet, $12 million.[19] These structures are constructed in shipyards and are towed to the well site where they are deballasted and fastened into place with pilings. No underwater fabrication processes are necessary for their construction or placement.

In several cases, however, platforms have been damaged during towing or installation and in these cases underwater repair techniques have proven valuable since the cost of refloating and towing these structures back to drydock was saved.[26,27] In addition, these structures may be damaged in service by wave action, fire or other operational accidents, as well as the corrosive action of the marine environment over a period of years.

For a number of years, from 1947 when the first platform was put in service, until the late 1960's, operators were reluctant to order underwater repair of these structures since single pass, drag type welds made underwater using the SMA process were of notoriously low quality. Any repairs made using this process were low in strength and notch toughness and suffered from cracking problems.[61]

Offshore platforms are complex structures and joining systems used in their repair must be able to overcome several constraints in addition to those encountered in all underwater fabrication processes. Since platforms are constructed of a combination of vertical, horizontal and diagonal members of varying sizes, any repair technique should be flexible, capable of repairing any member of any platform. High cost habitats designed for one configuration, such as those used in the repair of undersea pipelines are virtually ruled out by this requirement. Since welding operations conducted in an actual marine environment require expensive diving and surface support, any underwater repair process must be relatively quick. This eliminates processes with extremely slow deposition rates such as plasma-arc welding. Since offshore production and drilling platforms are critical structures subject to extreme loading conditions, weld quality is especially important. Cracking and low notch toughness cannot be accepted. Thus the conventional single pass underwater SMA process cannot be considered satisfactory.

Possible candidate processes for platform repair are thus considerably reduced. Small fixed and movable chambers employing the GMA process have been used with some success in the repair of tubular offshore structures. Although repairs which can be made to some joint designs are limited by the size of the head, this process appears to be sufficiently versatile for most platform repairs. Presently utilized mostly in depths of less than 200 feet, this process seems to be a good candidate to be developed for use at the greater

depths required for the repair of future platforms.

Another process, the multi-pass SMA technique developed and practiced by CBI has proven extremely reliable in actual service. Depth related capability seems to hinge on electrode composition and practical diving limits. E6013 electrodes have proved to be effective at depths exceeding 200 feet for materials with a carbon equivalent of less than 0.40. Austenetic electrodes are reliable in service to 80 feet for materials with a carbon equivalent greater than 0.40 but less than 0.60 and these electrodes are presently being modified for greater depth capability.[25,27] The greatest disadvantage of the multipass technique is the extremely exacting, time consuming and expensive training procedure needed to train welder-divers. It appears unlikely that personnel can be trained in the numbers required by a rapidly expanding petroleum industry.

Two other processes, shrouded metal-arc welding and wet GMA welding, which are in the experimental stage, exhibit promise but require much more developmental work before they can be considered operational.[10]

All of the processes mentioned as suitable for platform repair are highly diver dependent and thus are limited by depth and cost considerations as discussed in the next chapter. Mechanical joining is the only technique suitable for platform repair which is capable of employment by a manned submersible or remotely operated manipulator.

2.1.2 Subsea Production Systems

As the search for gas and oil progresses into deeper waters new production sites are required. Although the deepest fixed production platform now under consideration is planned for water depths of 1000 feet it is expected that a technical need to produce in 2000 to 3000 feet of water will soon exist. In fact, the record water depth for conventional gas and oil drilling is 2150 feet and rigs are now available which are capable of drilling in 3000 feet of water. Subsea production systems are now being developed and tested in order to meet the need for deep production facilities. In areas with rough weather conditions, subsea production sites are also expected to be more economical than platforms in waters as shallow as 400 to 500 feet.[22]

Underwater completions have been made for more than thirty years in shallow water and at low pressure. More than 300 have been made in Lake Erie alone and at least 106 have been completed on offshore continental shelves. However, the deepest of all these completions was made in only 375 feet of water, well within diver range. In all cases but one, divers were required to complete connection of flowlines even though attempts were made to connect several remotely. In addition, most production functions for these completions were performed on land or on nearby platforms.[22]

Subsea wellhead equipment or "X-mas trees" can be divided into "wet" and "dry" types. The wet type has all components exposed to the sea and must be repaired and serviced by either recovering the tree to the surface, employing conventional divers, or using specially designed

manipulators. The dry type has all components housed in a chamber isolated from the sea. This system can be serviced by men working on the seafloor in a one atmosphere environment. Though others are being constructed, only one dry system has been installed on a real subsea well.[2,15]

The wet tree is usually completely assembled and tested prior to installation. It can be run down to the seafloor casing housing and latched on with a remotely operated hydraulic connector. Flow lines can next be connected by divers or, at least theoretically, by remotely controlled manipulators. The dry chamber system is run down and connected to the seafloor casing housing in the same manner. However, all components are dissassembled and stowed inside until after connection to the casing. A specially designed one atmosphere capsule is used to transport men down to the chamber to make the flowline connection and assemble and test the X-mas tree.[15,22]

Four companies are presently constructing or testing complete subsea production systems with design depths ranging from 1500 to 3000 feet. It is estimated that one of these, Exxon's submerged production system (SPS), will cost about $29 million.[2] Two of the four have already been installed at test depth and the other two are scheduled to begin testing in 1975. Test depths range from 170 to 250 feet. Each of these four systems is designed so that repair or replacement of well head components can be easily completed.[22] In the wet systems all components are mechanically connected so that remotely operated manipulators or manned submersibles can replace faulty

components.[2,22] In the dry systems men working in one atmosphere chambers can effect repairs using conventional surface techniques.[15,22]

Although each of these systems contains structural protective members and other components which cannot be mechanically replaced or serviced from work chambers, the incidence of damage to, or deterioration of, these parts is expected to be very small. If some critical member should be damaged, it may be possible to reinforce it using a sleeve or other mechanical connector placed using a submersible or remotely operated manipulator, since water depths of 2000 feet and deeper are well beyond practical diving limits. If damage is severe enough to warrant closing down production, the entire structure must be retrieved and repaired on the surface or in drydock. Underwater welding systems capable of reliable repair work at ambient pressure on a structure 2000 feet below the surface are still quite a few years in the future. The need to design around technical gaps such as this one is the reason that deep subsea production systems are such complex and expensive projects.

2.1.3 Undersea Pipelines

Any offshore petroleum production system requires pipelines to bring any oil or gas recovered to some central collection point. Flowlines, transfer lines, trunklines and risers are all needed. In addition, underwater pipelines have become integral parts of transport pipeline networks used to route liquids to markets. A $475 million undersea pipeline system is presently being planned which will

carry crude oil produced in five North Sea fields to a terminal in the Shetland Islands. Called the Brent System, this pipeline will stretch 96 miles through waters over 500 feet deep and will eventually fill over one half of Great Britain's petroleum needs.[57]

Since the 1940's in the Gulf of Mexico, offshore pipelines have been constructed and laid from barges. In very shallow water, pipe sections are joined on the barge and passed directly over the stern to the bottom. As depth increases, rigid "stingers" or slides are used to support the pipe between the barge and the seafloor. In 1963, Shell Oil Co. developed a method where the pipe is held in tension at the barge and allowed to hang in a suspended span from the end of a short stinger to the bottom. Articulated stingers, an improvement developed in 1967, are sufficiently flexible to absorb lay barge motion and conform to suspended pipe span profiles.[22]

The largest pipeline laid in deepwater to date is the 32 inch diameter Forties Field pipeline, constructed for British Petroleum in the North Sea at water depths to 420 feet. It is thought that a dynamically positioned lay barge, using the tension technique, can lay pipe up to 24 inches in diameter in 3000 feet of water. With further development of tensioning equipment, laying 30 inch pipe at 3000 feet may eventually be possible.[22] In order for oil to be economically produced in waters exceeding 3000 feet, sizable quantities must be present. In such a case, floating risers might be employed to bring the oil directly to the surface and the need for bottom laid pipe eliminated. If underwater fabrication processes can be

developed to join pipe at extreme pressures without the need for divers, these techniques might prove to be less costly than riser systems.

The problems associated with construction of deep undersea production systems and pipelines are complex and difficult. However, the repair of pipelines in water depths beyond the reach of divers may be the single most difficult problem in extending oil and gas production into deep water.[59] At present, the system used for most underwater pipeline work is the hyperbaric chamber. Since a pipeline has a very simple configuration, it is possible to construct dry chambers which can be fitted over and sealed to pipes of many different diameters. Second generation chambers can be mated with alignment devices and used to join sections, to effect tie-ins and to replace sections of pipe in addition to performing simple repairs. Pipelines can be repaired, tested and coated, all within these chambers.[10,23] Since water is displaced from these chambers by a mixture of pressurized gases, men within these chambers are subject to a pressure corresponding to water depth. This method is thus limited to depths equivalent to practical diving depths.

An alternative repair method has been proposed by Shell. This system is called the Seafloor Pipeline Repair System (SPRS) and its development is being supported by other companies as well as Shell. The concept entails constructing an entire system, unmanned and remote controlled, which would replace entire sections of damaged pipe in a single dive. The system contains tools and manipulators necessary to uncover, inspect, clean, cut and remove damaged pipe and to insert and join replacement pipe, which is carried onboard. Mechanical couplings would be used for the joining of the replacement pipe to the pipeline.[29]

2.2 Deep Marine Salvage Needs

The requirements for metals joining processes in deep marine salvage are somewhat limited in scope. To begin with, salvage operations in waters deeper than 200 feet are somewhat rare and can be expected only in somewhat unusual circumstances. In such deep waters no attempt is likely to be made to salvage conventional ship types since required lift capacity would be prohibitive and structural integrity of the sunken vessel questionable. In addition, few vessels are expensive enough to justify the tremendous salvage costs involved and valuable cargo from a sunken vessel can be recovered by itself.

Deep marine salvage can then be expected to be limited to small objects except for two special types of cases. The first of these is the case of a fairly large object which possesses a great deal of structural strength and is very expensive. The second case is that of an object which has generated a great deal of international political interest. One example, the nuclear submarine, falls into both of these categories. It is conceivable that a submarine could be sunk on a continental shelf or other location at a depth shallower than its crush depth. Salvage would then be desirable for several reasons. First the submarine might be restored to service condition saving several hundreds of millions of dollars in replacement cost. Next, it is possible that if the submarine were sunk on the continental shelf of another nation its nuclear powerplant might stir up diplomatic reactions. Finally, it might be desirable to salvage the submarine to preclude the possibility of its recovery by another nation.

The establishment of an attachment point on a sunken object

constitutes the main need for underwater joining technology in deep marine salvage. This can be a difficult problem in deep salvage operations. Low visibility, diver stability, short bottom time and the problems inherent in the conventional manual SMA process can make the welding of a padeye, even in depths within the range of a diver, a difficult matter. In depths beyond practical diving limits, an entirely different approach must be taken.

The U.S. Navy is currently interested in developing a process capable of remotely attaching a 50 ton padeye to a metal structure underwater. Several devices are presently being developed to meet this and other deep sea attachment needs. These include exothermic welding devices, explosive bonding devices, velocity powered stud guns and automatically activated metal-arc processes. The velocity powered stud gun, in particular, has proved useful in various underwater tasks and is being used in multiple groupings to provide a lifting point in the Navy's Large Object Salvage System (LOSS). However, none of these devices has yet proved successful in providing heavy loading capacity using only one attachment point.

2.3 Other Needs

Industries other than the petroleum industry are just beginning to commence the development of marine resources. Due to this fact, it can be expected that much of the technology required by these industries will be adopted from the petroleum industry and newly emerging marine industries will not exert a large driving force on new technology.

The mining of manganese nodules from the seabed is a topic which is receiving a great deal of publicity. Several large corporate structures have invested millions of dollars in the development and testing of recovery techniques and processing plants. Surveys indicate that these nodules, which contain nickel, copper, and cobalt in addition to manganese, are most plentiful on the deep abyssal plain in depths ranging from 10,000 to 20,000 feet. At the present time, however, the legal status of mining these deposits is in doubt, depending on the outcome of complex international negotiations in the continuing Law of the Sea Conferences. This legal uncertainty has acted to inhibit capital investment in recovery equipment. In addition, these nodules, which form from mineral deposits in the water column, are spread in a fairly shallow layer over the seabed, although they are more concentrated in certain areas than in others. Because of this scattering, it is unlikely that any permanent seafloor structures will be erected to aid in the collection of nodules. All recovery is expected to be undertaken from surface based air-lift dredges and continuous line buckets possibly combined with bottom crawlers.[19] As a result, equipment is expected to be easily recoverable to the surface for repair and it appears unlikely underwater metal joining processes will be required.

Phosphorites are another important hard mineral mined from subsea deposits. However, land and shallow water deposits are sufficient to provide for world demand for some time so that deep water mining is not contemplated.[19]

One other conceivable need for metals joining in the deep ocean is the construction and repair of manned habitats used for scientific or military purposes. Although some far-sighted individuals have predicted the eventual construction of undersea cities, present activity in this field is somewhat more limited. Most if not all habitats are constructed on the surface and are recoverable for reuse. Since most are used as bases for saturation diving, repairs can be made using the diver operated techniques described for use in the repair of oil platforms. Any habitats constructed in deeper waters in the near future are likely to be small portable structures designed for missions of limited duration and, as a result, will require few, if any, repairs.

2.4 Summary of Needs

In summarizing those processes which appear to have potential for deep sea application, it is useful to divide processes into two groups. The first group encompasses those techniques oriented toward general repair or fabrication usage. Processes in this group normally require manned operation, either in the form of a diver or a welder within a dry habitat. The second group includes processes most useful in establishing single attachments on underwater bodies, such as the welding of a padeye underwater. Techniques in this group lend themselves much more easily to remote operation by a manned or unmanned submersible with manipulators.

Promising joining techniques are outlined in Table 2-1. In the first group, joining processes identified are all electric-arc welding processes, with one exception. In order to adapt these processes for

Table 2-1

Joining Processes with Potential for Deep Ocean Application

Process	Possible Deep Ocean Application
I. Processes Suitable for General Repair and Fabrication	
wet shielded metal arc	
single-pass	temporary repair; padeye attachment
multi-pass	platform, habitat, pipeline repair possible underwater fabrication
hyperbaric chamber (enclosing diver and work)	pipeline repair and hot-tap work fabrication of deep pipelines
small fixed or movable chamber (enclosing only work)	platform and other repair work
shrouded metal arc	presently under development
wet plasma arc	presently under development
wet gas metal arc	presently under development
mechanical joining techniques	platform, submerged production system, pipeline repair
II. Processes Suitable Primarily for Establishing Attachment Points	
exothermic welding/brazing	attachment point; possible pipeline repair
explosive welding	attachment point
velocity power tool	attachment point

deeper application, technical problems associated with pressure effects on the arc must be studied. In addition these processes require very precise manipulative ability and are thus not readily adaptable to remote operation. Both of these topics will be discussed in detail in later chapters. The one technique in this group which is not a welding process is mechanical joining. Since mechanical methods are compatible with remotely operated systems and are not affected by pressure, their use is being planned in several deep water systems.

Processes in the second group are somewhat more diverse in character. Each is technically different and must be studied separately. Little trouble is expected in matching these techniques with remotely operated diving systems.

The offshore petroleum industry is the driving force propelling the development of processes in the first category. Although there are certainly political forces acting on the industry, incentives motivating the development and employment of underwater joining devices are strictly economic. Operating costs offshore are so huge that the cost of developing and operating a joining process is completely subordinate to the goal of keeping hugely expensive capital equipment in operation.

Processes in the second category are most useful in deep salvage systems. The U.S. Navy is the primary organization conducting developmental work in this area. In a normal funding climate, money available for the development and operation of salvage systems can be expected to be modest. However, as is the case with all defense funds, spending can be subject to political pressures in response to interna-

tional events. Operations such as the salvage of nuclear weapons off Palomares, Spain, in 1966 or the salvage of a portion of a Russian submarine off Hawaii in 1974 can trigger the expenditure of vast amounts of funds for salvage systems.

CHAPTER 3 DIVING SYSTEM LIMITATIONS

Underwater joining techniques are highly dependent on the diving systems with which they are used. In shallow water, many problems such as low visibility and a lack of stability are imposed by diver limitations. As water depths increase, diving systems impose even stricter constraints on joining processes. The next few paragraphs outline the most important of these limitations which will be discussed in detail in the remainder of the chapter.

Topics of key importance include manipulative and depth limitations. Most of those processes which appear to have potential in meeting broad deep ocean repair and fabrication needs require manipulative abilities which can only be met by a trained welder. Thus, these processes can only be employed with a diving system which directly interfaces the man and the work. Unfortunately, the most useful of these diving methods expose the operator to ambient pressure which acts to severely restrict depth capability. Automatic processes such as those used to establish attachment points are much more versatile in this respect. Less manipulative ability is demanded and, as a result, these techniques can be employed with remotely operated manipulators as well as with divers.

As the distance from the surface increases, providing support functions for underwater tasks becomes more difficult. In shallow water, cables and hoses can be used to provide power and shielding gases for joining processes. At depths of several thousand feet, other solutions may become necessary.

The primary costs associated with actual underwater repair and fabrication operations are generated by the expense of diving and surface support. In addition, economic factors may be the determining consideration in the selection between different diving systems at some depths. Cost versus depth relationships for the various diving methods are thus necessary in gaining an understanding of the economic constraints acting on the total system.

A summary of diving system limitations is given in Table 3-1 at the end of this chapter.

3.1 Diving System Classification and Description

Since it is the purpose of this chapter to study diving systems as they impact on the joining of metals underwater, it is appropriate to classify them in a manner which is compatible with the classification of underwater joining processes. Diving systems of interest here can be divided into two groups in this manner. The first group is composed of those systems which have a direct man-work interface, that is those in which the diver/operator can get his hands on the work. In the second group are those systems in which extra links have been added in the form of manipulators, TV cameras or other similar devices. These systems have a remote man-work interface.

In the remainder of this section the following diving systems will be discussed:

Direct Man-Work Interface	Remote Man-Work Interface
Conventional Diving	Manned Submersibles
Saturation Diving	Remotely Operated Work Vehicles
Ambient Pressure Chambers	
Constant Pressure Chambers	

3.1.1 Conventional Diving

A conventional diving system is one in which a man is exposed to ambient water pressure, but not for a period long enough for his body tissue to become saturated with inert gas. The man may be tethered to the surface and receive his breathing gas through a hose from the surface or he may be free swimming, carrying compressed gas in tanks. For work projects in one location, the tethered arrangement is by far the most common. The diver's range of vision and manual dexterity are often poor, suffering substantial performance degradation compared to his counterpart on dry land. Short mission capability and generally shallow depths characterize conventional diving, with decompression required after only a few minutes of work below 100 feet. When air is used, a safe depth limit is just under 200 feet, with a helium-oxygen mixture it is less than 400 feet. At these limits, working time is extremely short if massive decompression times are to be avoided. Surface support required is minimal, consisting of a breathing gas supply, a line tender, a backup diver and a decompression chamber.[47]

3.1.2 Saturation Diving

The tissues of a man who has been exposed to an inert gas under pressure for 24 hours have taken up practically all the inert gas they can hold at that pressure. The man is then said to be saturated at that pressure and his decompression time is unaffected by further bottom time at that depth. A total saturation diving system permits the diver to live and work at pressure continuously for the entire time the job may take, requiring only decompression when the diver leaves the system. In this manner, a much larger percentage of the time under pressure is spent working and a much smaller percentage is spent undergoing decompression.[47,64]

A given job can often be completed more quickly and with fewer divers if saturation techniques are used rather than multiple conventional dives. However, surface support requirements are increased quite a bit both in cost and complexity due to the requirements for a large pressurized living chamber and a heavy lift capability. These increased costs must be balanced against any advantage gained by an increase in depth capability or time saved when choosing between conventional and saturation methods.[64]

An actual undersea test project was conducted to determine if men could work at a depth of 840 feet effectively. Using saturation techniques, divers were kept in a living chamber at 660 feet and deployed to the work site for periods of up to three hours, where they conducted work simulating that which might be required at a subsea wellhead.[17] From the results of this test it can be concluded that men

can now work in waters in excess of 800 feet safely, at least in ideal conditions. Although men have recently undergone pressurization in dry chambers to pressures corresponding to 2000 feet of water,[1] the jump from experimental to practical working conditions is a large one. It is widely predicted that men will work almost routinely in waters of 1000 to 1200 feet by 1980 but, at the present time, tests under ideal conditions not withstanding, 600 feet is a pretty good estimate of a practical working limit in a severe marine environment.[38,47,64]

3.1.3 Ambient Pressure Chambers

Several commercial diving companies, engaged in the support of offshore oil production, use underwater welding chambers to provide a dry environment for the repair of damaged sections of undersea pipelines. The forward and aft bulkheads of the chamber, perpendicular to the pipeline direction, are designed with large grooved penetrations and the bell is lowered so as to fit these directly over the pipe. Below the pipeline, once it is straddled by the bell, the grooves are closed with watertight doors. Next, water is displaced from the chamber by pressurized gases and divers enter from the bottom and fold down gratings for a work platform.[47]

The gas mixture used in these chambers must be non-explosive and able to sustain life for brief periods in case of diver life support system malfunction. A helium-oxygen mixture with an oxygen partial pressure of 6-8 psi has been found suitable. The welders breathe through a mask using a separate system of gases more suitable for sustaining life. Because the chamber is extremely humid, hydrogen

cannot be removed from the chamber atmosphere and shielding gases must be used with the welding arc itself.[23]

Entire pipeline repair and fabrication systems can be built around the basic chamber. These systems include fine positioning and alignment equipment so that large sections can be joined without intermediate short sections called "pup joints."[23]

Since welders are at ambient pressure in these chambers, safe diving depth limits must be observed. The Taylor Diving Company has utilized one of these chambers at 540 feet in the Gulf of Mexico, which is the deepest known use.[63] Support requirements for these systems are complex and costly and are quite similar to those for saturation diving.[23]

3.1.4 Constant Pressure Chambers

Subsea chambers maintained at a constant internal pressure of one atmosphere are one solution to the problem of working on underwater producing systems in deep water. These chambers can be constructed to enclose clusters of conventional oil field equipment on the sea floor, including manifold centers, separation stations and pumping stations as well as wellhead X-mas trees. Designed to mate with personnel transfers capsules, these chambers can be used by petroleum company work crews to complete welds and perform on site maintenance. Since personnel are not exposed to pressure or other diving hazards, workmen specially trained in oilfield skills but not in diving can be employed. Surface repair techniques and welding processes can be employed with little problem. Special equipment within the chamber

need not be developed since men can work on the equipment directly. This ability to work directly on production systems also means that response to unexpected problems within the chamber can be more flexible and imaginative.[15]

The one atmosphere chamber is the only diving system with a direct man-work interface which is not severely limited in depth capability. Its primary disadvantage is that it is extremely limited in application. Work can only be performed in very small areas enclosed by a specially designed work chamber which can only be mated with a custom designed transfer capsule. The system is also expensive, considering its limited application, and surface support requirements are heavy, similar to those for ambient pressure chambers and saturation diving. At the present time, three companies are designing and testing this type of system. Two test models have been deployed in waters of 240 to 250 feet. Present chambers are designed for depths of up to 1200 feet but with design modifications these systems can be extended to 3000 to 4000 feet water depths.[22]

3.1.5 Manned Submersibles

The word submersible, as it is used today, connotes no precisely defined vehicle. For the purposes of this study, a manned submersible will be considered any undersea vehicle capable of transporting a man or men at a constant pressure and capable of performing some degree of manipulative work underwater. A great deal of literature has been generated describing these vehicles,[13,24,32,34,47,67] so only the briefest of remarks will be noted here. There are a great many such devices

of varying complexity in service today and more are being designed and built. Submersibles are being used to complete a variety of underwater tasks in governmental, commercial and scientific service and are indispensible to expansion into the deep ocean. These work vehicles are important here because they represent a means by which joining processes can be deployed and operated in a number of situations in the deep ocean. Actual operation must be conducted remotely through manipulators, but men can directly observe and control such actions from within the submersible. Submersibles can be designed for use at any depth. In fact, several can reach into even the deepest ocean trenches. Submersibles with manipulative ability are being built for use on the abyssal plain at depths of 15,000 to 20,000 feet.[47] Limits, as they affect joining techniques, are not depth-related but rather determined by the manipulative devices incorporated into submersibles. This is the subject of a later section. Present working submersibles have limited mission durations and require extensive support from an accompanying surface vessel.[13,47]

3.1.6 Remotely Operated Work Vehicles

Remotely operated work vehicles may be used effectively underwater in a number of situations. Manipulators can be operated from the surface as well as from within a submersible and television cameras and sonar systems can go a long way toward replacing a man's eyes underwater. Although the advantage of having a man, particularly one with special skills, present at an undersea work site may be useful or even essential, that advantage still has its price in terms of

risk to life, money, and mission flexibility. Manned undersea vehicles must incorporate extensive life support systems which are not only costly but also limit mission duration.[14,33]

Several remotely operated maintenance systems which are intended to perform predesignated functions on underwater structures are being designed. These include Shell's Seafloor Pipeline Repair System (SPRS) and Exxon's Submerged Production System (SPS) maintenance unit. The SPRS is designed to replace a section of pipeline, an action which might remedy a number of problems. The SPS maintenance unit is designed to remotely replace removable components on the production system.[2,59] Remotely controlled devices may also prove useful in several phases of deep salvage work, such as attaching lifting points and lines to sunken objects. The use of remotely operated vessels to recover weaponry underwater is now well advanced.[33] Remotely operated work vehicles may not be as flexible in unusual situations as manned submersibles, but they should prove useful in a number of tasks, saving the high costs and personnel risks associated with the use of manned vehicles.[33,67] These devices can be built to operate at any desired depth, but require a surface platform for control and power supply.[14]

3.2 Manipulative Ability

The ability of a diving system to perform its intended task, in this case the operation of a joining process, is the key issue under examination in this chapter. There is a sharp difference in the manipulative ability of systems with direct man-work interfaces and those with remote interfaces. Direct interface systems are capable of

operating any of the joining processes listed in Table 2-1. Remote interface systems are, at present, capable of deploying only those systems in part II of this table as well as mechanical joining devices. All of the direct interface systems but one are severely depth limited, however, and the one not depth limited is restricted to use only in very limited circumstances. The logical question one must then ask is: What are the chances of developing manipulative systems capable of performing advanced underwater joining techniques?

Manipulator systems, whether manned or operated from the surface, must contain four integrated subsystems: locomotion, sensory, command and manipulation.[14] A diver, in fact, can be thought of as an extremely well integrated model of such a system. In order for the overall system to function properly, each of the components must do its part. The locomotion subsystem must maintain the position of the larger system with respect to the workpiece. The sensory subsystem must relay an accurate picture of the operation as it progresses to the command subsystem, which must control the manipulator itself. The more fully integrated the overall system, the greater the underwater efficiency.[13] A study of the relative productivity of alternative diving systems illustrates this point. A man performing a task on land is given an index value of 1.0 for relative productive capacity and other representative values are as follows:[67]

saturation diver	0.6
conventional diver	0.5
manned submersible	0.05 - 0.25
remotely operated vehicle	0.01 - 0.05

Values follow the degree of subsystem integration. Human divers are extremely well integrated. In manned submersibles, sensory and command systems are both incorporated within the operator but these subsystems are more loosely joined to the locomotive and manipulative subsystems. In fully remote vehicles, subsystems are least tightly integrated and manipulative ability suffers accordingly.

In another study, overall performance ratios for a series of eight underwater tasks indicated a 4:1 advantage for divers over submersible-type manipulators during tests in which the operators could see the work. For tasks requiring particularly exacting manipulations the advantage for divers rose as high as 30:1.[49]

There has been much work on perfecting underwater manipulators in recent years and technology from aerospace and nuclear handling has been incorporated into the effort. In spite of this fact, manipulative systems still lag far behind men in their overall work ability. This point is well documented by experimental tests, both on land and in water environments.[49,67] It seems unlikely, then, that these techniques will become sufficiently advanced in the near future to perform delicate arc-welding processes underwater. This is emphasized by the fact that only the most well trained, experienced divers are presently able to perform joining techniques of the quality necessary for permanent repair and fabrication usage.

If devices with remote man-work interfaces cannot be used to arc-weld underwater, of what use are they in joining metals in the deep sea? Can their virtually unlimited depth capability be used to advantage? These devices have tremendous potential for application

in the deep ocean, but suitable joining techniques must be designed especially for these systems, exploiting their advantages and minimizing the effects of their limitations. Remotely operated work vehicles and submersibles are being used in the design of systems for the maintenance of submerged production systems and pipelines underwater. Joining is being accomplished in these systems by the use of mechanical connectors which are designed to be compatible with both the work vehicle and the system to be repaired. Submersibles and work vehicles could prove very useful in placing and activating automatic welding devices which may be designed to fill certain underwater requirements. Several examples illustrate this possibility. First, devices are under development which may prove suitable for providing necessary attachment points for salvage purposes. These include exothermic, explosive bonding and velocity powered techniques. Other conceivable possibilities include semi-automatic shielded metal-arc techniques, which might be used for attaching padeyes or applying temporary patches, and exothermic welding or brazing techniques which might be used to seal repair sleeves to underwater pipelines. More detailed descriptions of these examples are included in a later chapter.

3.3 Support Systems

Many underwater joining processes require a source of electrical power and some of these processes require shielding gases as well. In relatively shallow waters, these items can be provided by cables and hoses from the surface. As depths increase, however, these simple

solutions may no longer be feasible.

Most manned submersibles are designed to operate without a tether leading to the surface. Much more maneuvering freedom is gained in this way and undesirable surface coupling effects are eliminated. These vessels are presently powered by batteries with very low power densities. Both weight and volume are at a premium on the majority of these vessels as well.[24,47] If joining processes are to be employed with presently available manned submersibles, they must either have small self contained power sources or only modest requirements from the submersible itself. In the future, such power sources as fuel cells, radioisotope systems, and small nuclear power plants may increase the power available to untethered submersibles somewhat. Joining systems with fairly small power requirements will still be most desirable, however, since any power gained will be largely absorbed into submersible propulsion and auxiliary systems. Small quantities of shielding gas may be carried by these submersibles in cylinders mounted outside the pressure hull, but joining processes must use these gases only sparingly.

The majority of remotely operated work vehicles in use today are tethered to the surface and power as well as guidance is provided through this tether or umbilical. Power requirements for joining processes are therefore much less restrictive if remote vehicles are employed, even though cable losses are significant as illustrated in Figure 3-1.[24,33,61] It is still more practical to carry shielding gas in cylinders on remote work vehicles due to the pumping head required at extreme depths for a hose system.

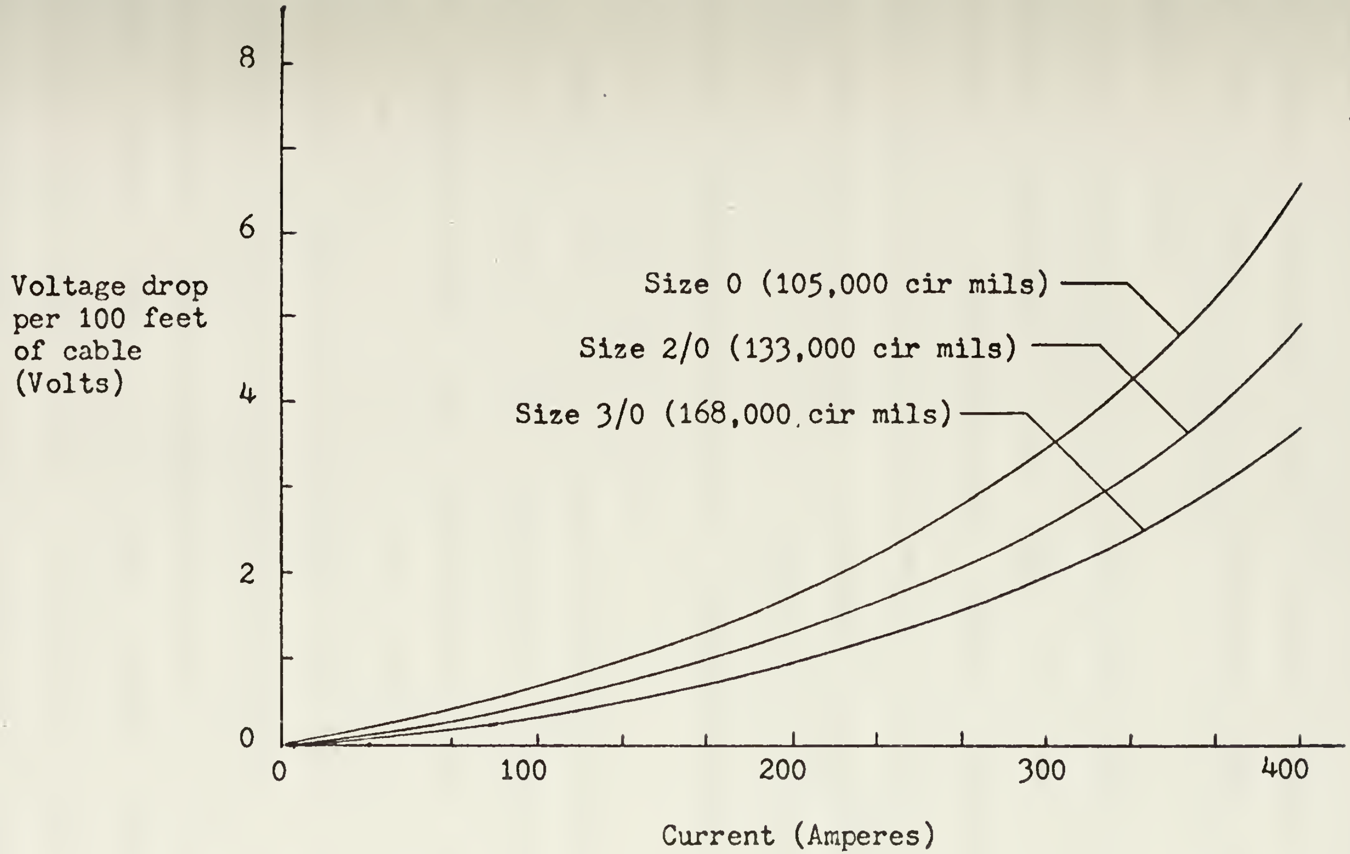


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Figure 3-1 Voltage Drop in Power Supply Cables

3.4 Cost-Depth Relationships

The major operational cost components of any total underwater joining system are the expenses associated with diving. Costs incurred by the operation of the joining process itself are normally quite small. This is particularly true for deep water systems since diving costs increase rapidly with depth while process costs increase only slightly, if at all.

In many cases, selection of a diving system must be based on performance considerations alone. Depth constraints and manipulative limitations act to narrow the choice of diving systems considerably. However, cost considerations will enter into the choice in a great many cases so that a knowledge of cost-depth relationships is essential. It should be emphasized that data presented here necessarily represents only general trends and that specific trade-offs should be based on precise data for individual systems.

Figure3-2 presents cost relations for depths of up to 1000 feet and Figure 3-3 presents similar information for depths of up to 20,000 feet. Hyperbaric chamber costs, which are not shown, are somewhat higher than those of saturation systems operating at the same depths. One atmosphere chamber costs are largely undetermined at this time but should approximate those of manned submersibles. One major factor which affects the relative position of the curves is the cost of surface support equipment. This figure is highly variable, depending upon the particular support vessel chosen. In interpreting these figures it must be remembered that no attempt has been made to adjust the curves

Figure 3-2 Cost vs. Depth for Diving Systems (0-1000 feet)

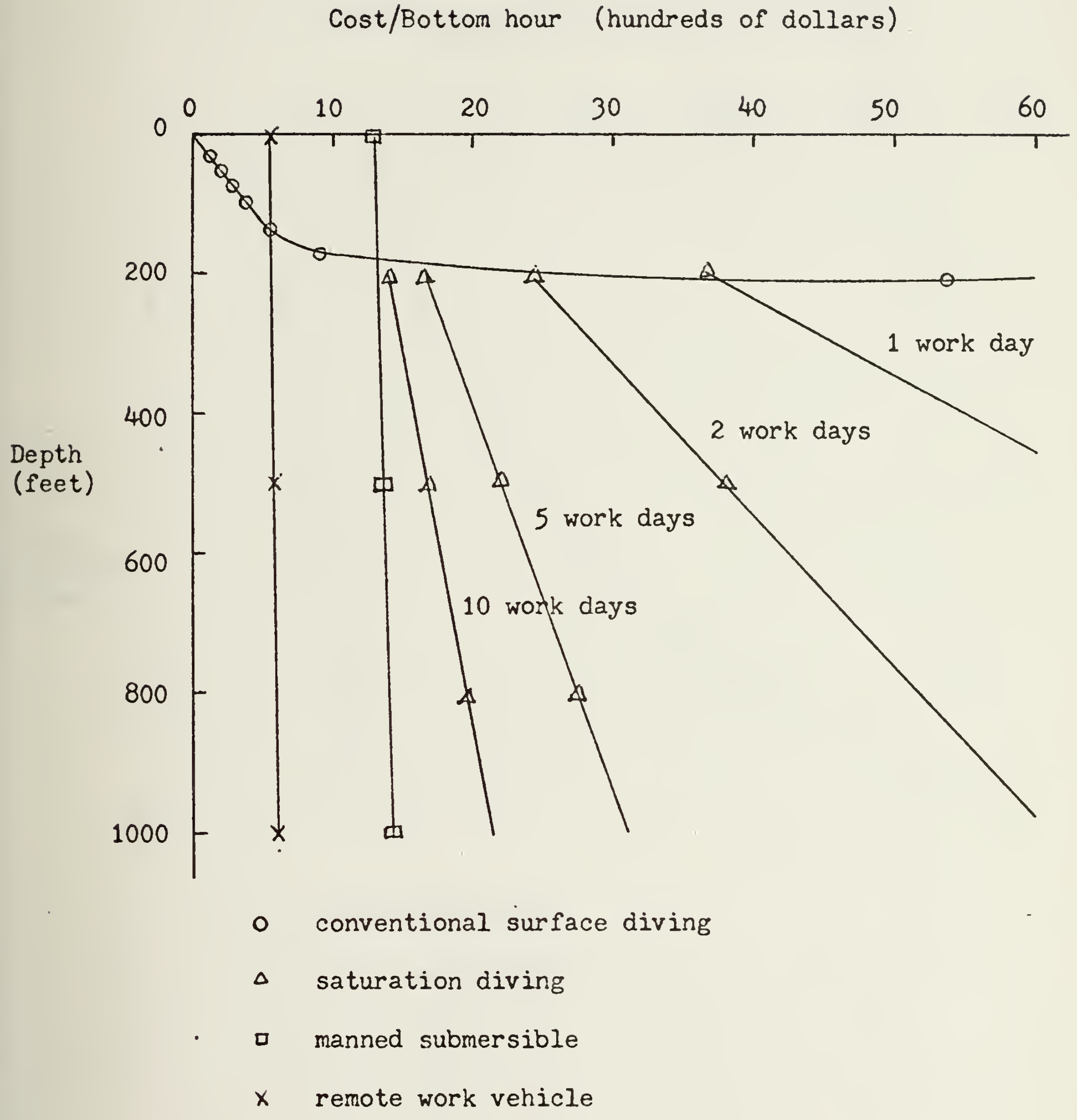
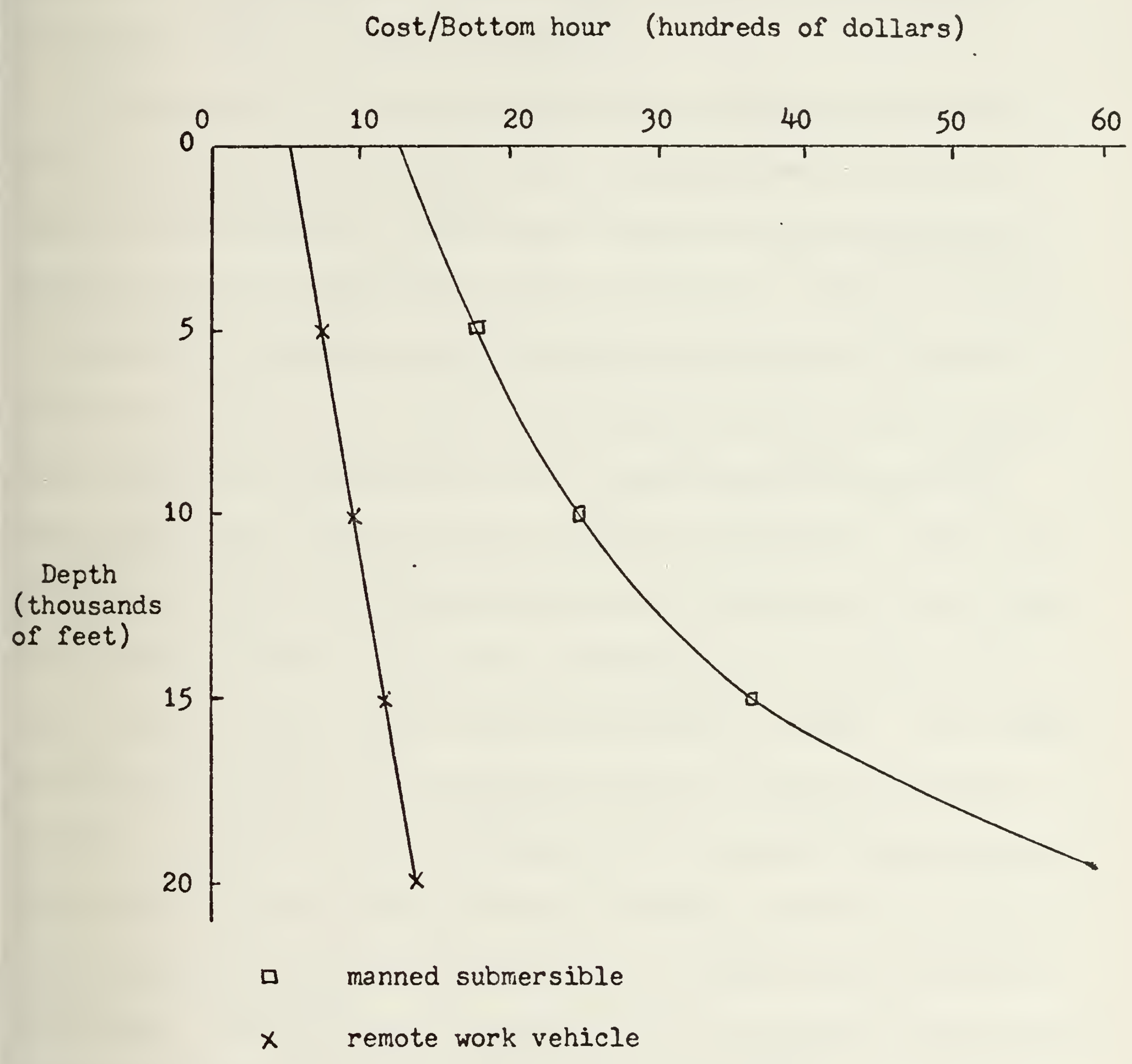


Figure 3-3 Cost vs. Depth for Diving Systems (0-20,000 feet)



to account for the relative efficiencies of the systems under comparison. As a result, both cost per work hour and hours required to complete the job must be considered in determining the most economical diving system for a particular job. Supporting data and calculations for Figures 3-1 and 3-3 appear in Appendix A.

In Figure 3-2 it can be seen that conventional surface diving techniques have no real competition in shallow water, at least for tasks of short duration. This is due to the fact that support and capital costs for conventional systems are small. However, as depth or bottom time increases, larger decompression debts are incurred and the conventional diver must spend a greater portion of his time under pressure in decompression and a smaller portion in working.[47] Conventional diver efficiency also decreases with depth. Depth does not, however, make as much difference in the efficiency or work cycle of a saturation diver. He needs to orient himself to depth and the job at hand only once so his overall efficiency is higher. The number of work hours per day in a saturation system is largely unaffected by depth. At 300 feet, the saturation diver can spend approximately three times as long working, per unit time under pressure, as can the conventional diver and his efficiency will be 25-50 percent more at this depth. This increase in working time and efficiency makes up for increased support costs for jobs of longer duration.[64]

Due to a marked difference in capability, manned submersibles and remote work vehicles are rarely in competition with conventional and saturation diving systems.[13] As both Figures 3-2 and 3-3 illustrate,

cost increases with depth are much less dramatic for these systems. Several "standard" submersibles for relatively shallow depths can be purchased, but remote systems and many submersibles are one-of-a-kind models and are still more expensive than they would be if they were more widely produced. This accounts for the relative closeness of the two curves. As remote work vehicles become more standardized their cost in comparison with submersibles should drop.[14,47]

Manned submersibles are most economical for missions lasting a few hours because performance and time on bottom are limited by on-board power. Remote vehicles are particularly valuable for long missions in very deep water and in the performance of tasks inherently dangerous to divers and submariners. No price tag can be put on human life.[14,24,33]

Table 3-1

Summary of Diving System Limitations

Diving System	Manipulative Ability	Depth Capability	Flexibility	Support Capacity	Risk to Life
Conventional Diving	3	1	5	3	6
Saturation Diving	4	3	6	4	5
Ambient Pressure Chambers	5	2	2	5	4
Constant Pressure Chambers	6	4	1	6	2
Manned Submersibles	2	5	4	1	3
Remotely Operated Work Vehicles	1	6	3	2	1

6 greatest

1 least

CHAPTER 4 DEPTH-RELATED TECHNICAL PROBLEMS

As operating depths are increased, the effects of pressure on joining processes become of far greater importance. Although a certain amount of work on this topic has been done, a great deal more must be completed if greater joining depths are to be achieved. In this chapter, technical problems anticipated in extending the depth capacity of those techniques outlined in Table 2-1 will be reviewed. An assessment of possible corrective measures as well as an identification of practical future developmental work will be made.

Many of the arc-welding processes which appear in Table 2-1 are subject to the same depth-related problems due to the characteristics of the underwater arc itself. These common problems will be dealt with first. Following this, the other processes noted in Table 2-1 will be examined in order to define technical problems which must be solved in expanding operational depth limits.

4.1 Electric Arc Processes

A welding arc is a sustained electrical discharge through a high temperature, high conductivity column of plasma. It is produced by a relatively large current, in the neighborhood of 200 amperes, and a low voltage of from 35 to 50 volts. The plasma, through which electrical conduction takes place, contains a radiating mixture of free electrons, positive ions and some highly excited neutral atoms. The electrons drift toward the anode and the ions toward the cathode. Electromagnetic forces constricting the arc determine this drift velocity. Since the majority of the arc power (75 to 90 percent)

is delivered to the anode, the workpiece is most often made the anode and the electrode the cathode in underwater welding. Termed straight polarity, this arrangement takes advantage of the high density, high velocity, electron bombardment of the anode for heating.[54]

In addition to electromagnetic forces, an underwater arc column is compressed by hydrostatic forces and cooling effects. These hydrostatic forces are, of course, a function of depth. Cooling effects are caused by the surrounding water as well as by hydrogen dissociated from the steam in the welding bubble. Further, the arc may be geometrically constricted by the cathode spot or electrode in straight polarity welding.[10] All of these forces combine to increase the rate of collision among electrons, ions, and neutral particles, causing a high pressure region. Also, in order to continue the mechanism of current transfer, the conduction cross section must be maintained. Therefore, if conducting forces restrict the arc area, the core temperature must increase to maintain the current. Core temperatures can range from 5000 to 50,000°K depending on the degree of ionization and arc constriction.[54]

The special characteristics of an underwater arc create a number of depth-related effects which must be considered in the development of any electric arc joining process for the deep sea. These effects are discussed in the following sections.

4.1.1 Penetration and Weld Bead Shape

The very high arc core temperatures found at greater depths greatly increase arc penetration. This can have both beneficial and detrimental

effects. Increased penetration, accompanied by more rapid metal transfer, can lead to higher, more efficient deposition rates. On the other hand, at the high pressures found on the deep ocean floor, increased penetration can lead to burnthrough.[54]

In laboratory research, Madatov reported an increase in penetration with depth for shielded metal arc (SMA) welds, as well as widening of the penetration shape factor (W/P) from 5 to 3.[40] De Saw et al. found that reverse polarity SMA welds were shallower, wider and less porous than straight polarity welds.[18] This reversal of arc characteristics at depth was not explained. However, during extensive commercial repair work at sea, Grubbs has noted that excessive penetration is not a problem in multipass SMA welding, even at depths in excess of 200 feet.[26]

SMA weld bead characteristics have been found to be quite satisfactory in actual service when the sophisticated multipass technique is employed. Developmental work in extending the depth capability of this process centers around electrode coatings and has resulted in the development of satisfactory electrodes for low carbon steel (carbon equivalent less than 0.4) welding in depths exceeding 200 feet. At present, austenitic electrodes may be satisfactorily employed for steels with higher carbon equivalents in depths up to 80 feet and work is underway to extend this capacity to over 300 feet.[25]

A number of investigators have studied the effects of pressure on the gas metal arc (GMA) welding process. Pilia found that welds made at 60 feet were peaked and thin and that burnthrough was a problem at 80-100 feet because of excessive penetration.[10] In dry welds made

under pressure on aluminum, Brandon noted that the weld cross sectional area, the weld depth to width ratio and penetration all increased with increased pressure. Careful control of filler metal feed speed was the single most important factor available to offset or control these effects. Arc voltage and welding travel speed were less influential in their effects on weld penetration and shape.[9] In underwater chamber welding, the diver-welder must manipulate the arc differently than in surface welding in order to offset the more narrowly concentrated heat of the constricted arc. It is more difficult to initiate the arc, to maintain a stable arc and to obtain good fusion across the width of the weld joint. The welding arc becomes more intense and the electrode wire melts at a faster rate as the pressure increases. This causes a larger weld pool and control difficulties, and can lead to such weld defects as overlap and improper fusion.[45]

As welding pressure increases, the only significant change in the characteristics of a gas tungsten arc (GTA) is a constriction of the arc column leading to an increase in arc voltage. This causes an effect not unlike that of a plasma arc weld and results in greater weld bead penetration, often as much as 50 percent at 20 bar.[36]

4.1.2 Current and Voltage

Compressive forces acting on the underwater arc make voltage-amperage curves concave or rising. Thus, though the voltage needed to strike the arc is higher than the voltage needed to maintain it, the amperage grows as the voltage decreases once the arc has been established. As depths increase and greater constriction due to water

pressure is experienced, the current density continues to increase.[10] At great depths, Madatov found the large concentration of heat from the increased current density acted to limit welding currents to 180-240 amps.[40]

Although, at one time, apparent increases in current requirements for SMA welding were attributed to heat losses through thermal conduction,[30] it is now believed by some researchers that increased current demands are primarily due to the constriction of the arc and increased resistance heating of the rod as greater pressures are encountered.[54] Arc length must also be considered, since longer arc lengths result in greater hydrogen cooling and hydrostatic effects, which combine to cause greater constriction and current density. To compensate for these factors, it has been suggested that the welding current be increased by 10 percent per atmosphere of additional pressure in order to maintain similar arc conditions.[7] This suggestion has not been confirmed by practical experience, however. During multipass SMA repair welding at various depths up to and exceeding 200 feet, Grubbs has found no need to increase current drastically with depth. He has found that it is necessary to increase current approximately 10 percent over that required for air welds and to increase current as cable length is increased but has noted that there is no need for a current increase with depth.[25]

Several reports have been issued on the effects of pressure on the GMA welding process.[8,9,12,48,51] From them, much information concerning the effects of depth upon current and voltage can be gained.

Arc power consumption is a meaningful measure of welding performance which complements voltage and heat input data. An idea of the arc power consumed in any region can be gained by measuring the voltage consumed and remembering that the same current flows through all elements in a welding circuit. These distinct voltages, which are shown in Figure 4-1, are the IR drop in the electrode stickout, the anode voltage, the positive column voltage and the cathode voltage. Since total arc voltage will be divided differently among these regions depending on welding conditions, these distinct voltages must be considered. Figure 4-2 illustrates arc length vs. voltage. The IR voltage drop can be expected to remain constant and not vary with minor current variations. Extrapolating the curves to zero length eliminates the contribution to total voltage of the column voltage. These zero arc length voltages, which represent the sum of anode and cathode voltages, increase with pressure by differing amounts as shown by the varying slopes of the constant pressure curves.[48] Similar results were reported for underwater arcs by Avilov in earlier work.[7]

This increase is probably due to anode voltage, as can be explained by using the following formula for direct current reverse polarity melting rate:[48]

$$M = aI + bLI^2$$

where: a is a constant dependent upon anode size and material

b is a constant dependent on electrode diameter and resistivity

L is the electrode strickout distance

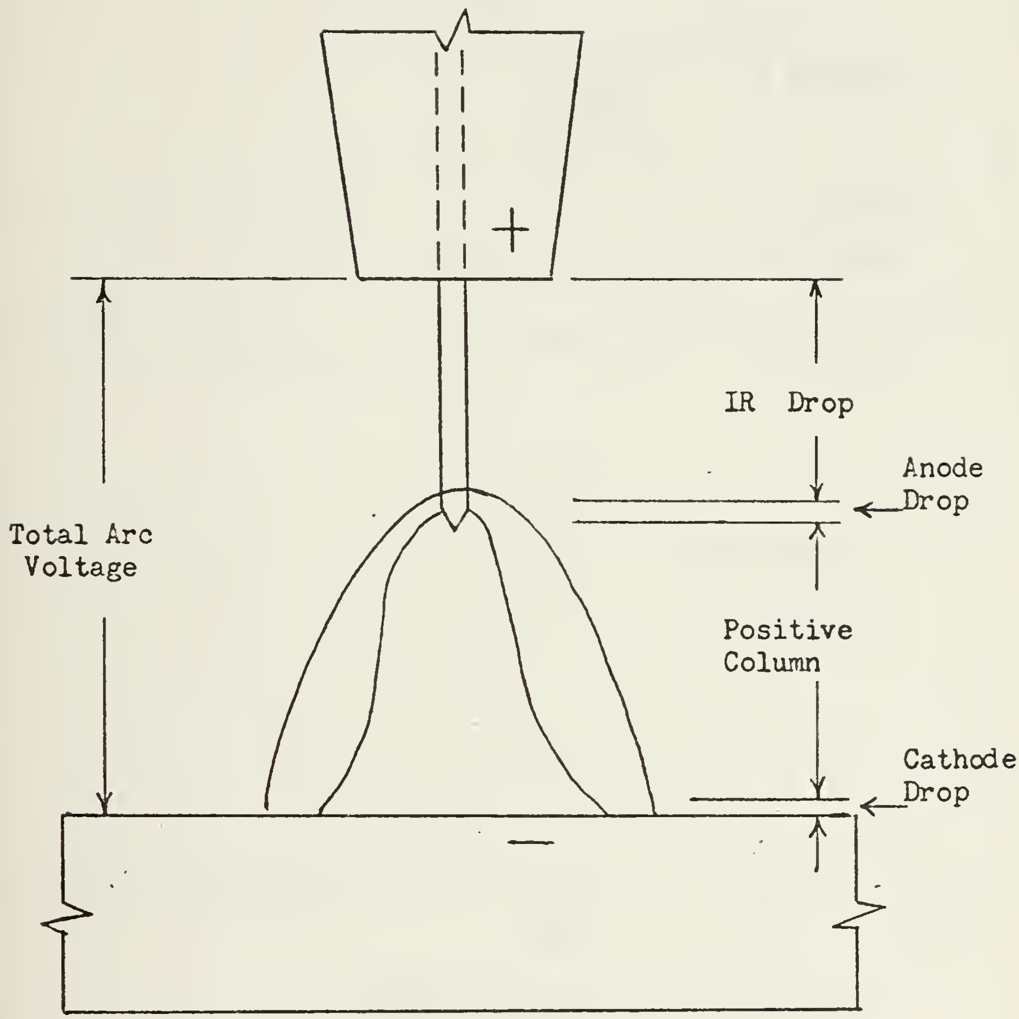


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Figure 4-1 Arc Voltage Division

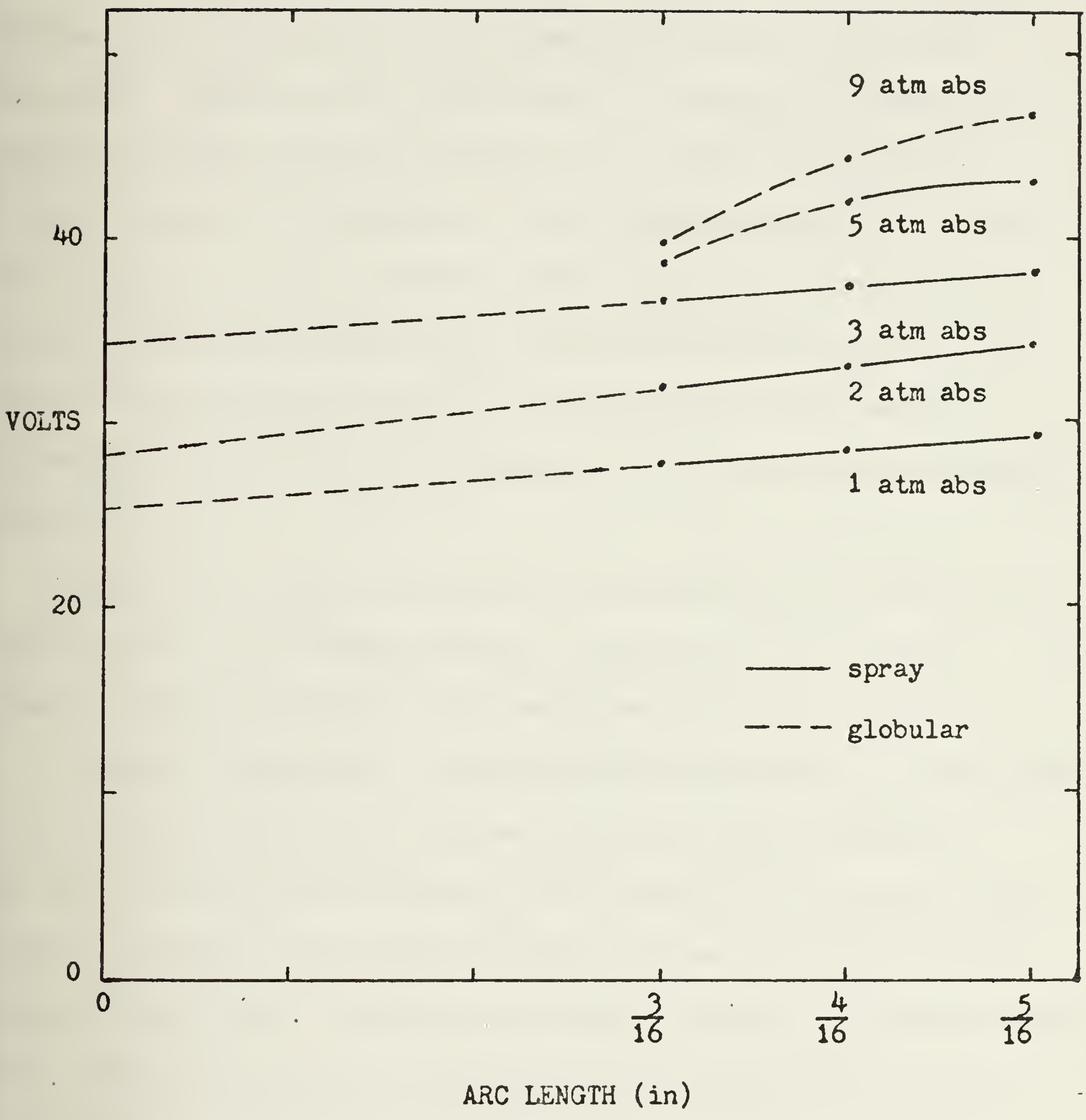


Figure 4-2 Arc Length vs. Voltage[48]

The first term on the right represents the anode melting contribution and the second, resistance melting. In this equation, the electrode voltage drop is independent of the temperature at the end of the electrode. Experimentally, more current is required to maintain the melting rate than would be predicted by the melting rate equation. Since no change can be expected in the resistance heating term, the anode melting term must increase. This conclusion is supported by Maecker's analysis of plasma jets. Entrained cold gas has to flow over the electrode to be heated and accelerated. This energy requirement should result in an increase in the anode voltage drop with pressure.[48]

Figure 4-3 presents voltage and pressure data for the same arc length values in a different manner. Figure 4-4 is the power vs pressure relation calculated from measurements of arc voltage.[48]

Brandon,in his report, noted that increased pressure is detrimental to arc stability, but that increased voltage promotes stability. At low pressures, near atmospheric, arc stability is relatively insensitive to voltage, but at high pressures, increased voltage greatly increased stability.. This acts to reinforce previous work which suggests that increasing voltage when ambient pressure rises may be a useful technique.[9]

Several experimentors discovered that constant potential power sources were not adequate for work at higher pressures. Drooping power sources were used at pressures greater than about 8 bar to provide the necessary open circuit voltage for high pressure welds.[12,48]

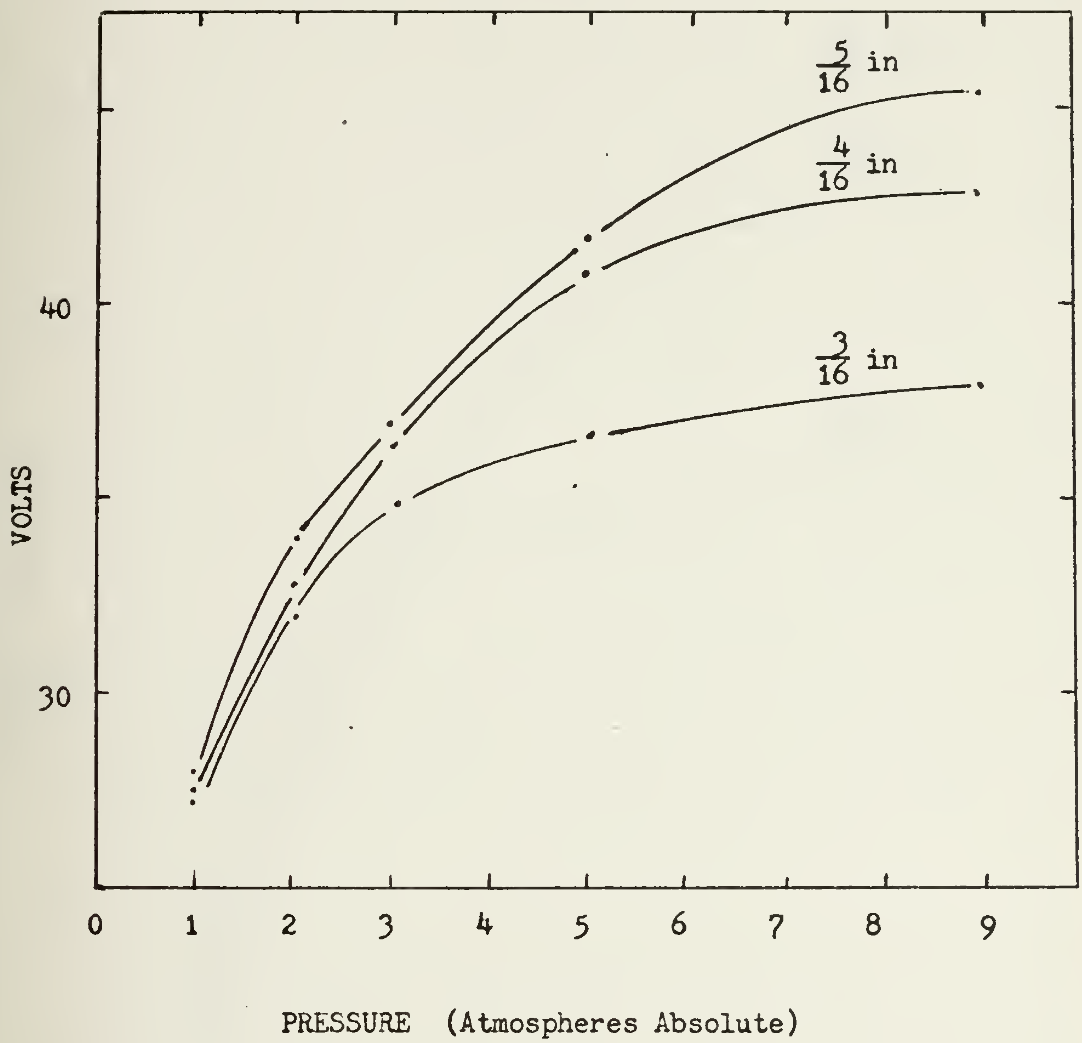


Figure 4-3 Arc Voltage vs. Pressure[48]

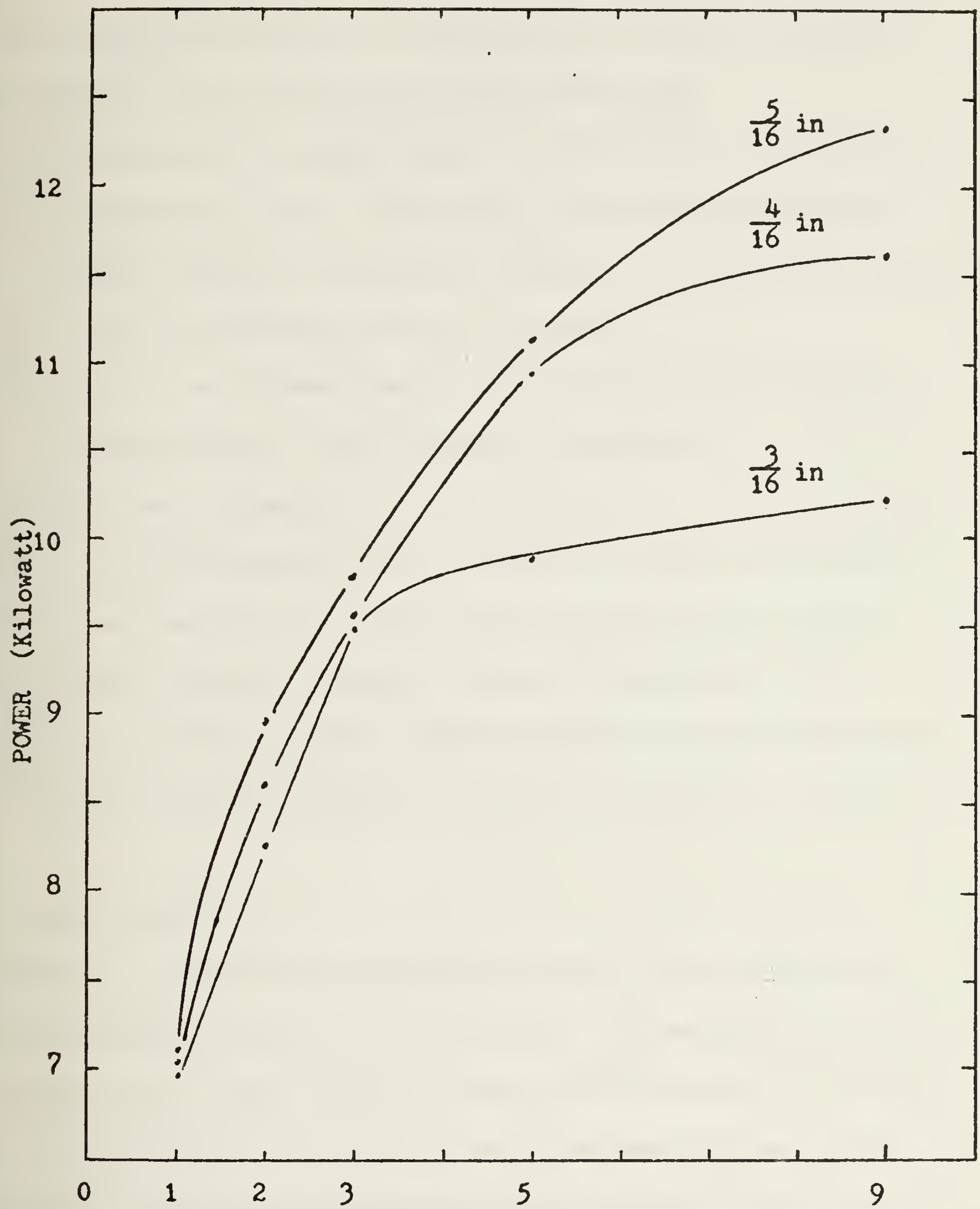


Figure 4-4 Arc Power vs. Pressure

In summarizing current and voltage relations found in welding under pressure, the following points should be noted:

1. As hydrostatic pressure adds to electromagnetic and cooling constricting forces, the current density increases and a higher voltage is required to maintain a constant arc length.
2. Power requirements increase with depth.
3. Current requirements may increase somewhat with depth but the magnitude of this increase is in question.

Further work is needed to clear up areas where confusion exists as well as to verify previous work. Whenever possible, such work should be undertaken in an actual ocean environment, over a wide range of actual undersea projects. Results which appear to be significant in laboratory tests conducted under carefully controlled conditions are often not important factors in actual marine work.

4.1.3 Metal Transfer

There are three basic modes by which metal from the electrode can be transferred across to the weld pool. The one which occurs at the lowest current level is dip or short circuit transfer. In this mode, electrode feed rate, current, and power source dynamics are such that the metal transfers across during the short circuit and, in the remainder of the cycle, the arc is maintained without metal transfer. As the current is increased, other parameters remaining the same, the transfer mode shifts to globular or drop transfer and the metal is transferred in large drops that travel slowly to the

workpiece. This shift occurs because the ohmic heating of the electrode and the anodic heat developed at the tip generate enough heat to permit large globules of metal to detach without short circuiting. As current is increased further, rapid melting of the electrode occurs and droplets are ejected as a fine stream or spray by the action of plasma jets. In globular transfer, gravity is the dominant force, in spray transfer, the strength of the plasma jets is dominant. These modes may undergo transformations from one to another as parameters are altered or may occur in combination.[12]

Maecker's plasma jet theory is useful in explaining the effects of pressure upon transfer in the spray mode. As the arc is constricted, radial pressures increase. Pressure equalization causes a flow along the axis toward larger cross sections and lower current densities. This flow draws cold gases into the arc and further constricts the discharge cross-section at the electrode, increasing the pumping action. This process continues until the temperature gradient becomes steep enough for a steady state to exist. The steady plasma jet attracts current paths by its good conductivity. These paths supply enough joule heat to offset the conductive cooling of the plasma jet and the balance is maintained.[48]

As ambient pressure rises, the thermal conductivity of the gases increases. This increased conductivity causes a constriction of the arc and a new, higher velocity steady state is attained. This results in an increased drop transfer rate and deeper penetration, up to a certain level. At sufficiently high pressure levels the combined

effects of the reflected vapor jet from the workpiece and a pressure induced squeeze effect on the bottom of the arc column begin to retard the plasma flow rate. This causes an eventual reversion to globular transfer.[48] Figure 4-5 illustrates the balance between arc plasma and hydrostatic forces.[10]

In studies of the effects of pressure on the GMA process, Billy and Perlman et al. found that a reversion from spray to globular transfer occurred at sufficiently high temperatures. The arc also became unstable resulting in an excessive amount of metal vapor and spatter as well as an uncontrollably large weld puddle. Poor, highly crowned weld beads were also formed after reversion to globular transfer.[10,36,48] Burrill and Levin also found that there was a marked trend toward decreased metal deposition efficiency due to metal vapor formation and spatter. However, they could not confirm a change in the mode of transfer to globular. This may have been due to their use of a higher voltage power source.[12,36]

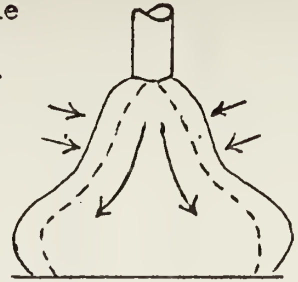
Figure 4-6 illustrates the increase of spray transition current and voltage with rising pressure for a GMA process.[48]

With the GTA process, arc instability does not arise since the wire is not part of the arc system but is fed and melted directly in the weld pool. The only significant change in the GTA arc with increased pressure is a constriction of the arc column which leads to an increase in arc voltage and penetration. At higher pressures the GTA weld is similar to one made by the plasma-arc process. The increased penetration may make it possible to increase welding speed slightly thus improving this process' chief shortcoming.[36,45]

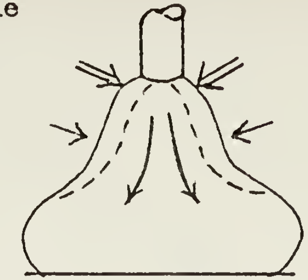
Figure 4-5

The Effects of Depth on Arc Characteristics[10]

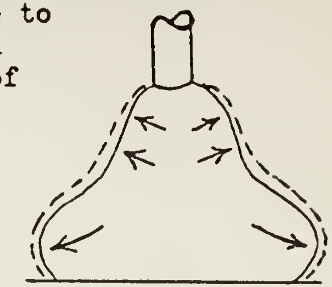
Constriction due to a rise in thermal conductivity.



Constriction due to cold gases drawn past the electrode.

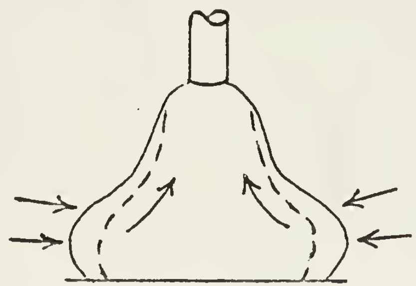


Expansion due to the increased temperature of the arc.

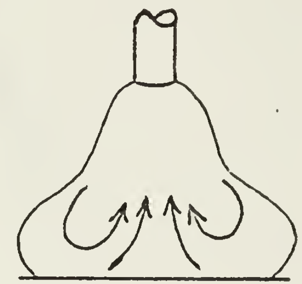


A. Forces acting on the top of the arc. The net result of these forces is a tendency for accelerated metal transfer and increased penetration.

Constriction due to ambient pressure effects.



Turbulence and reduction of flow caused by reflection of the plasma jet.



B. Forces acting on the bottom of the arc. The net result of these forces is a resistance to metal transfer and decreased penetration.

Forces A and B must be in equilibrium. When forces A predominate metal transfer is in the spray mode. As forces B become larger, the plasma jet is decreased until drop transfer replaces spray transfer.

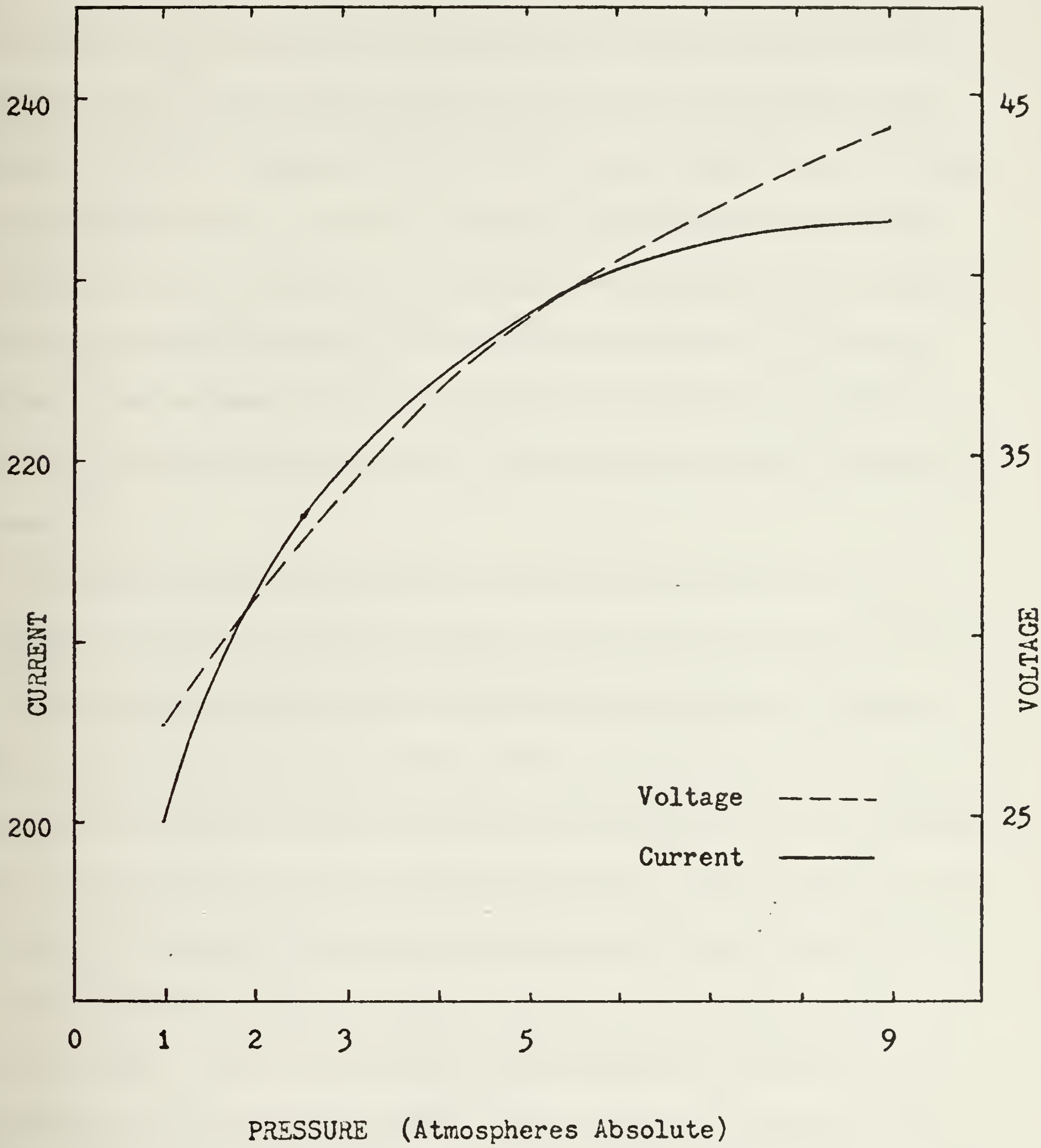


Figure 4-6 Spray Transition with Changing Pressure[48]

The normal metal transfer mode for SMA welding using the drag or touch method is small droplets, except for an occasional arc short circuit due to the formation of a large drop. Silva found that, even at shallow depths, SMA welding underwater resulted in globular rather than spray transfer.[10] Madatov found that the time taken to form a drop on the electrode and the time that the drop spends in the arc bubble atmosphere were about the same for the SMA process. This is in contrast to thin wire welding processes in which the time spent in the bubble atmosphere often exceeds the time spent in drop formation. Madatov found that SMA drops transferred at a rate of 44 per second during his experiments.[10]

In summary, increased pressure on the welding arc results in arc instability and a tendency to revert from spray to globular transfer. Increasing the voltage acts to prevent the revision to globular transfer, but does not prevent arc instability and the resultant loss of deposition efficiency due to spatter and vaporization. One suggested solution to this quandary is to employ lower heat input versions of the GMA process such as dip-transfer and the pulsed-arc technique.[45] In the dip or short circuit mode, the filler wire first shorts out to the molten weld pool. Next, the current surges and the filler wire is melted off and the arc reestablished. These shorts occur 50-70 times a second with metal transfer taking place during each short. In pulsed-arc welding, the reverse effect occurs. The filler wire melted by the arc is projected across the arc by the current which is pulsed at 60 times per second. Both of these processes involve heat inputs

20-30 percent lower than conventional GMA welding.[45]

A great deal of work has been done studying the mechanism of metal transfer in arc processes under pressure. It appears that many of the original questions in this field have been answered and the major problems isolated. Much work remains to be done, however, in solving these problems.

4.1.4 Bubble Dynamics and Shielding Gas

No results have been reported on the effects of depth on gas evolution rates. It has been suggested that this is an area that requires work in the future.[55]

The effects of increased pressure upon the weld bubble are fairly easy to determine by assuming that the bubble atmosphere is an ideal gas. Since the bubble atmosphere is predominantly hydrogen this assumption is acceptable for pressures and temperatures of practical significance. The volume of a gas bubble containing a given mass is directly proportional to gas temperature and inversely proportional to pressure:

$$V \propto \frac{T}{P}$$

As water depth increases, the pressure term increases. Increasing hydrostatic pressure also causes greater constriction of the arc resulting in higher current densities and greater arc temperature. This raises the temperature of the gas generated. Arc temperature does not increase as steeply as pressure, however, so the pressure

term dominates and the volume of the bubble decreases as greater operating depths are reached. This means that the protection afforded a SMA weld made without supplementary gas shielding will decrease.

Silva has developed relations which link the velocity and diameter of a rising bubble to its depth:[55]

$$V = \sqrt{\frac{4\,ghd\,(\rho_w - \rho_b) + 0.532d^2}{2\rho_b d + 3C\rho_w h}}$$

$$d = \sqrt[3]{\frac{p + \rho_w gD}{p + \rho_w gh}} \cdot d^3_D$$

where V = upward velocity (ft/sec)

g = acceleration due to gravity (ft/sec^2)

h = depth of bubble being considered (ft)

D = depth of arc (ft)

p = atmospheric pressure (lb/ft^2)

C = coefficient of drag for a sphere (dimensionless)

d, d_D = diameter of bubbles at h or D (ft)

ρ_w, ρ_h = mass density of water or bubble (slug/ft^3)

Increased pressure also affects shielding gas behavior. The density of the gas is increased and higher flow rates are required. Figure 4-7 illustrates the increase required by Burrill and Levin in their experiments.[12] Flow rates as great as ten times those used for

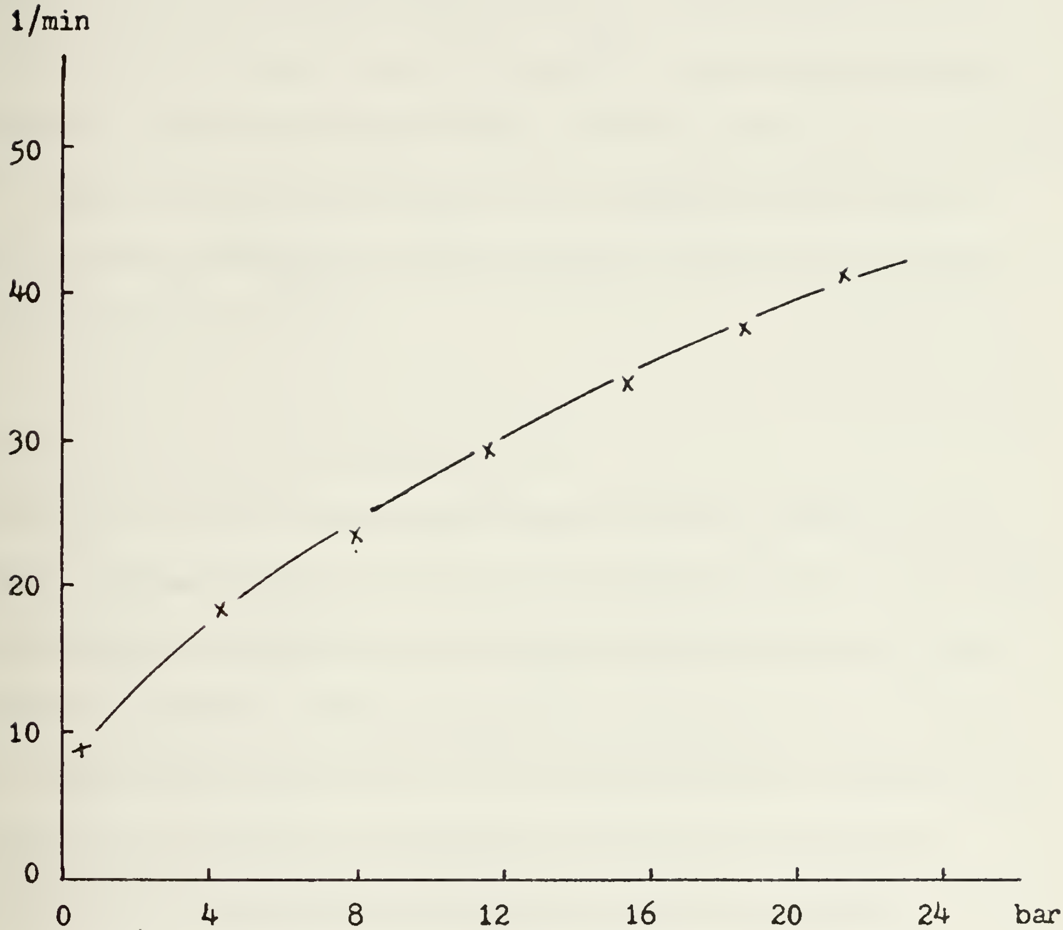


Figure 4-7 Increase of Shielding Gas Flow with Pressure[12]

surface welding have been required. Arc behavior may also change with depth and influence the selection of the shielding gas and the gas flow rate.[45]

Liquification of shielding gases places a depth limit on their use, since the torch would cease to function.[36] Of the gases suitable for shielding, argon and hydrogen remain gaseous at the greatest pressures. At $0^{o}C$, argon liquifies at 3570 meters and nitrogen at 5090 meters. Heating of a gas may extend its range slightly, but practical considerations limit this action.[54]

4.1.5 Porosity and Chemical Composition

Porosity is caused by small gas bubbles becoming trapped in the weld metal. The small hole, or pore, in the welded joint is a mechanical defect and is not as serious as the chemical problem associated with the presence of the gas. Having oxygen or nitrogen present is harmful because oxides and nitrides formed from these gases cause embrittlement of the metal. The presence of hydrogen is even more critical but its effects will be considered separately in the next section.[10]

Two possible causes of porosity in SMA welds made underwater have been suggested. The first, not a depth-related effect, is that porosity is associated with wet electrode coatings. Chicago Bridge and Iron welders have found that keeping electrodes dry in a special underwater case until they are actually placed in the holder results in high quality, porosity free welds.[25] Better coatings, which resist moisture penetration, also help to overcome this problem. There has

been speculation that increased porosity found in SMA welds made at greater depths is related to the shrinking of the protective gas bubble under high pressures. It is thought that protection of the arc and molten weld metal normally provided by the gas bubble breaks down.[45] This problem might be solved by using a shroud to trap shielding gases generated or by the use of supplementary shielding gas.

In GMA welding tests made under pressure, porosity was found to be reduced when pressure was increased. This is believed to be due to the fact that the gas pressure in the bubbles was lower than the sum of the hydrostatic pressure of the molten metal, the surface tension of the molten metal, and the ambient pressure of the chamber.[8,48] If this is the case, chemical problems will remain unchanged since the amount of gas in the weld is not changed.[51] Brandon noted a correlation between pore size and shape and turbulent arc and puddle action in GMA pressure welding. This might become a significant problem if pressures are sufficiently great to cause the welding arc to become unstable. In his tests, Brandon found that filler metal speed rate was the only parameter which affected weld soundness. Low filler metal feed rates with low levels of arc turbulence gave completely sound welds. High feed rates with a large amount of turbulence resulted in large voids.[9]

In underwater welding there are many hydrogen and oxygen ions present and the possibility of substantial numbers of sodium, chlorine, magnesium, sulfer, potassium and calcium ions from the dissociation of sea water. In addition if nitrogen gas shielding is used, care must be taken to avoid welding steels containing aluminum, chromium,

vanadium, or molybdenum since a brittle nitrided structure could result.[54]

The presence of oxygen in a weld will reduce strength, hardness and notch toughness, especially if dissolved in quantities greater than 0.1 percent. Since oxygen from dissociated water is so prevalent in underwater welding, deoxidants in electrode coatings become of critical importance.[10] As Table 4-1 indicates, a noticeable reduction in carbon, manganese and silicon is observed as welding is carried out at progressively greater depths. It is apparent that pressure increases the rate at which these deoxidants combine with the oxygen generated from the dissociation of water. This leads to their proportionate removal from the weld metal.[36] It has also been reported that the chemical activity of silicon and manganese deoxidants increases with an increase in pressure. In welds made in aluminum under pressure, Rabkin et al. found that the concentration of the easily vaporized alloying elements, manganesium and zinc, increased as pressure was increased. This was due to the elevation of their boiling points and to a corresponding decrease in their rates of vaporization from the weld pool. An increase in zinc and magnesium concentration resulted in the elimination of defects caused by oxide inclusions and in a reduction in porosity.[51]

4.1.6 Hydrogen Embrittlement

The severe quenching effect of the underwater environment and the presence of hydrogen in the weld area cause the most severe problems encountered in wet underwater arc welding. Although the quenching

Table 4-1 Changes in Weld Composition with Depth[36]

Depth (m)	Carbon (wt %)	Manganese (wt %)	Silicon (wt %)
20	0.26	0.63	0.16
40	0.19	0.21	0.08
60	0.09	0.12	0.03

problem can be solved for certain applications by removing the water through the use of dry chambers and shrouds, the remaining moist atmosphere is still high in hydrogen. Shielding gases are used to overcome this difficulty in chamber welding, but it remains a problem in shrouded SMA welding as well as in all wet techniques. The combined effects of hydrogen and the quenching action result in a severe cracking problem in the heat affected zone (HAZ) and in a loss of ductility and tensile strength.[11,36,45]

The quenching of the weld due to the large heat sink of the water is not a depth-related problem, but there are indirect depth effects. In the deep ocean the water is likely to be much colder than at the surface and the quenching effect is more severe.[54] Hydrogen embrittlement, which is depth-related, results in serious cracking only in hardened regions, such as those martensitic areas caused by quenching.[16]

An underwater arc operates in a bubble atmosphere resulting largely from dissociation of the water by the extreme heat of the arc. This gaseous atmosphere may be up to 93 percent hydrogen.[11] The hydrogen dissociated from water in the bubble dissolves into the weld puddle and the rapid quenching action which enhances the formation of brittle martensite by a precipitation process also acts to prevent the hydrogen's escape. As the temperature cools down, the solubility of hydrogen is reduced and the hydrogen begins to diffuse out of the weld metal into the surrounding water and into the HAZ. The presence of both hydrogen and a hard martensitic structure in the same region, the HAZ, is an important point since hydrogen will not induce cracking unless the

region is hardened and contains residual stress concentrations. Faster cooling rates and resultant higher hardnesses give the HAZ a higher susceptibility to hydrogen cracking.[52]

Hydrogen embrittlement is most apparent at temperatures just above those of the ductile to brittle transition of the hydrogen-free metal. Below the transition temperature, the metal is brittle regardless of the presence of hydrogen and above this temperature it is difficult for micro cracks to form and propagate before plastic deformation can occur.[16]

Although many theories have been developed to explain the mechanism of hydrogen embrittlement, the one advanced by Morlett, Johnson and Troiano[16] seems to be generally accepted today. This theory is based on diffused hydrogen localized at lattice inperfections known as voids. The severity of the embrittlement effect depends both upon the established stress system and the diffused hydrogen. The voids are regarded as micro notches about which a multiaxial stress system will be established when stress is applied to the steel. According to this theory, the stress system will be triaxial in nature in a region within the metal lattice near each void. It is suggested that it is the hydrogen concentration within this entire region of triaxial stress and not the concentration within the void alone that determines the degree of embrittlement.[16]

During diffusion, hydrogen concentrates in those regions of the lattice that are highly stressed. This creates a hydrogen concentration gradient which corresponds to the multiaxial stress gradient of the

region. However, once within the stressed region, equilibrium requirements cause the hydrogen to move from the lattice into the voids. The size of the hydrogen concentration gradient depends upon the original hydrogen concentration, the hydrogen diffusion rate and the time available for the diffusion of the hydrogen. One necessary condition for the diffusion of hydrogen through a metal is the dissociation of the hydrogen molecule to atomic hydrogen at the surface.[52]

The diffusivity of hydrogen in metal can be expressed as an equation of the form:

$$D = D_o \sqrt{P} \exp(-Q/2RT)$$

D = Diffusivity of hydrogen

D_o = Constant

P = Pressure of hydrogen

Q = Heat of solution

R = Gas constant

T = Absolute temperature

This equation, known as Sievert's Law, also governs the solubility of hydrogen[54] in the weld metal.

It can be seen that diffusivity increases with temperature in accordance with the exponential law governing rate processes, and that diffusivity is also proportional to the square root of the hydrogen pressure. The hydrogen partial pressure in the arc bubble must be nearly as great as hydrostatic pressure since the bubble is more than 90 percent hydrogen and must have a total pressure equal to hydrostatic pressure. Thus, as Figure 4-8 illustrates, for a given temperature, the percentage of hydrogen in the HAZ increases as the

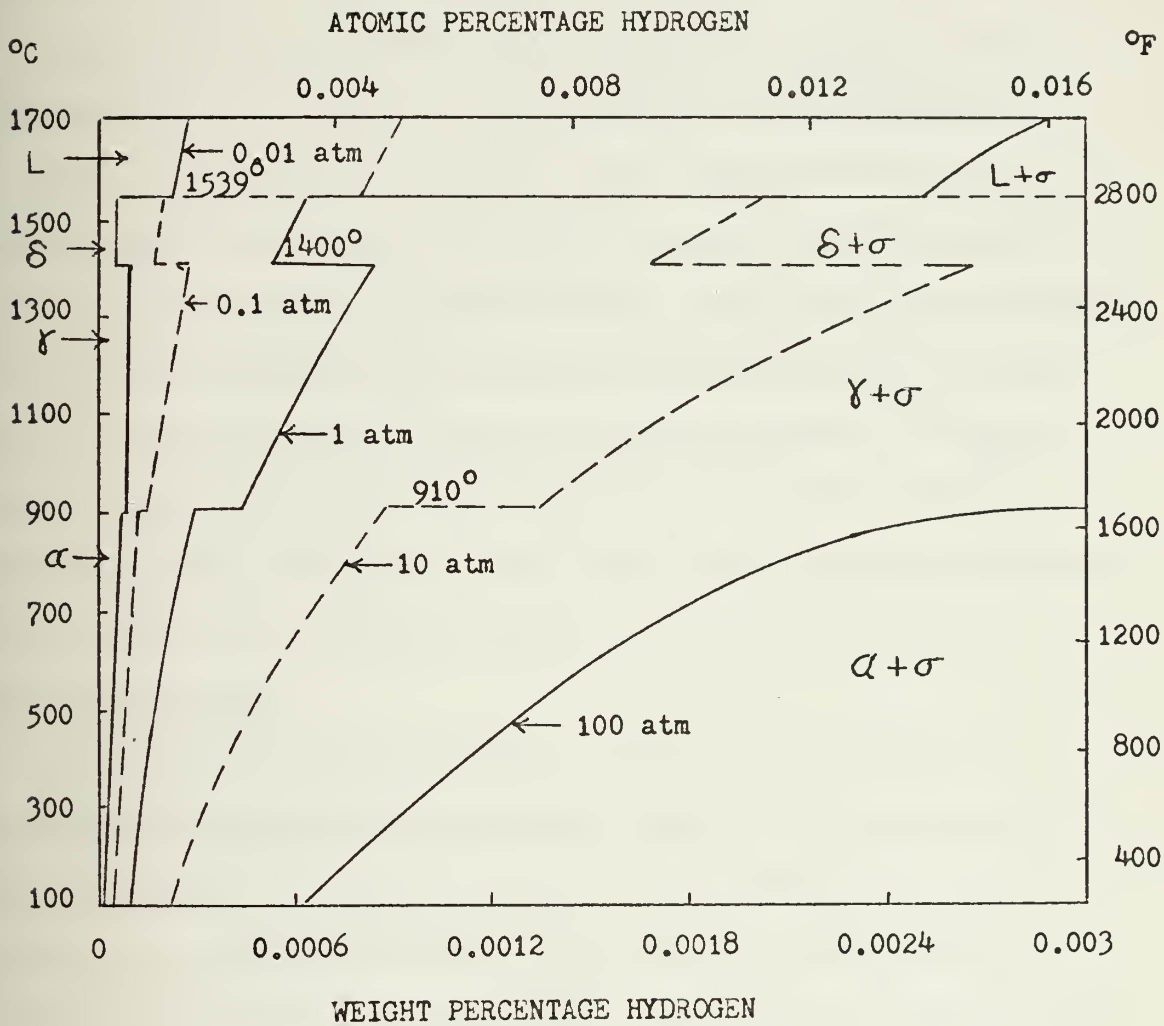


Figure 4-8 Iron - Hydrogen Equilibrium Diagram

pressure at which the weld is made is increased.

It has been suggested that the total amount of hydrogen which originally goes into solution in the weld metal must correspond to the maximum solubility of the metal. Since liquid metal has a greater gas solubility than solid, this results in greater initial absorption than would be expected using Sievert's Law. As a result, the diffusivity to the HAZ will increase over the values predicted by Sievert's Law. The rate controlling process for gas absorption proposed to replace Sievert's Law is the rate of gas ion supply to the metal surface.[54] Additional study to determine which of these two diffusivity relations is most useful in predicting the extent of hydrogen embrittlement should be undertaken.

Once embrittlement has occurred, a brittle micro crack may initiate in the region of high triaxial stress. The exact manner by which the hydrogen concentration causes crack initiation is unknown. In fact, it is not certain whether the initiation occurs prior to, or after, the introduction of hydrogen.[11] Once the micro crack has been initiated, its propagation depends upon the hydrogen concentration, the triaxial stress field and the plastic flow at the crack tip. The initiation enlarges to the size of a small crack which induces further stress on the crack tip, causing it to propagate. This crack may then grow in steps to critical size which can lead to brittle fracture and the resultant failure of the structure.[52]

In most cases, of course, hydrogen-induced cracking does not lead to catastrophic failure. However, offshore structures made of higher strength steel have often suffered less dramatic cracking problems

when repairs were attempted using single-pass wet welding techniques. It was not uncommon to be able to actually lift fillet welds made using wet processes out of the joint due to the severity of underbead cracking.[45]

Porosity, due to hydrogen coming out of solution and forming small voids in the weld area, can also occur. It is not a major problem in reducing the quality of welds made underwater. It has been found in experimental studies that increased pressure acts to retard the formation of pores in welds.[8,51] It is uncertain, however, whether this effect is due to the increased heat allowing the weld metal to remain molten longer, giving hydrogen additional time to escape, or to the increase in hydrogen solubility which results from increased pressure.[8]

Two approaches have been tried to lessen the effects of hydrogen embrittlement. In steels having a high carbon equivalent (greater than 0.4 but less than 0.6) the use of austenitic electrodes has resulted in the elimination of underbead cracking during multi-pass underwater welding. This technique has proven reliable down to a depth of 80 feet and research to extend this depth to the 300 feet mark is underway.[25] An austenitic weld metal microstructure is capable of storing large quantities of hydrogen which, it appears, keeps the hydrogen away from the crack sensitive HAZ, avoiding underbead cracking.[27] A certain degree of success has been noted using post heat treatments for underwater welds. Some welds showed significant improvement after two or three hours at 250°C but others required much higher temperatures.[36] In another case, aging at ambient temperature for two days produced an improvement in ductility which was attributed to the escape of

hydrogen from the weld area.[27] Another form of post heat treatment, tempering previous passes with later passes using multipass techniques has resulted in CBI being able to consistently produce high quality welds underwater.[27] It has also been suggested that preheating or insulating the work surface may help to reduce hydrogen related problems.[10] Other possibilities include increasing the heat input to the weld arc without increasing weld size through the use of a wet GMA technique.[10]

4.2 Exothermic Welding and Brazing

Exothermic processes exhibit several advantages which make them ideal candidates for application in the deep sea. Exothermic devices can be made which are small, inexpensive and contain their own power source. They can be placed either by submersibles, remotely controlled vehicles, or by divers and can be activated remotely. Several studies have been conducted on the feasibility of employing these devices for the placement of padeyes on objects prior to salvage.[5,42,44] In addition, it is possible that several other practical applications may arise since the mold in which the reacted thermit is cast is not strictly size or shape limited. One such possible application is the attachment of repair sleeves to damaged subsea pipelines.

An exothermic reaction is one in which metal oxides having low heats of formation are reacted with reducing agents which, when oxidized, have high heats of formation. Although there are many possible thermit reactions, the following is by far the most common:

$$3Fe_3O_4 + 8Al \qquad 9Fe + 4Al_2O_3 + 719.3 \text{ Kcal}$$

This reaction theoretically achieves a temperature of 5590°F but radiant heat losses and losses to the reaction vessel reduce this temperature to about 4600 °F. Additions and impurities further reduce the temperature of the filler metal to around 3800°F. A temperature of about 2200°F is needed to initiate the reaction and is usually provided by an ignition powder which is ignited by a spark or an electric device.[44]

The basic thermit reaction may be employed in one of several ways for joining. In fusion welding, the most common method, the thermit is reacted in a chamber and tapped into a mold only after the reaction is complete and slag separation has occurred. A portion of the molten metal flows completely through the mold and into an overflow chamber in order to provide for surface cleaning and preheating. The remainder is held between the surfaces to be joined by the mold and forms the actual weld. By employing appropriate molds, welds of various sizes and configurations can be accomplished.[5]

Pressure thermit welding utilizes the molten metal and slag to provide the necessary heat to join the surfaces, but not to add material to the weld. The heat content of the thermit products is used to bring temperatures up to the forging level, at which time pressure is applied to form a bond.[5]

Thermit brazing also uses the thermit mixture strictly for its heat content. After the parts to be joined are heated, a flux is used to clean the surface and a brazing material flows between the parts by capillary action.[45]

Just as in the more common arc technique, cooling rates have a

significant influence on the resulting hardness of a thermit fusion weld. Rockwell "B" hardness climbed considerably as the cooling rate was increased.[5]

The underwater environment has other effects on thermit processes. Water must be removed from the weld area prior to tapping any molten metal into the area if a sound weld is to be achieved. This may be accomplished by removing the water through displacement by a pressurized gas or by preheating the area through the use of a separate thermit reaction timed to ignite just prior to the primary reaction. It has been found that the flow of molten metal through the mold can effectively remove minor oxidation and dirt from the surfaces to be joined. Surface preparation may then be kept to a minimum.[44]

One major depth-related problem, offsetting the pressure differential between reacting chamber and mold in order to provide for the flow of molten metal, must be solved before thermit processes can be considered practical alternatives for deep ocean application. Surface thermit welding devices rely on gravity induced flow of the molten metal from the reaction chamber into the mold. In a confusing and crowded underwater environment, such as that found in many salvage situations, proper orientation of the device for gravity flow cannot always be assured. In addition, the mold is subjected to ambient pressures while the reacting chamber must be kept dry. The thermit reaction itself cannot be used to help offset this pressure differential since none of the products of reaction are gaseous. As a solution to this problem, pressurizing the thermit reaction chamber to a level

slightly higher than ambient pressure, prior to leaving the surface, has been suggested.[5] It is hoped that the slightly greater pressure in the reaction chamber will then be sufficient to overcome the ambient pressure and to induce flow of the molten metal into the mold. In order for this method to work properly, however, the level of pressurization will have to be calculated rather precisely. If chamber pressure is too low, no flow will occur; if too high, the mold may be damaged or forced off the surface. Measuring the exact depth at which an attachment point is required also adds complexity and expense to a salvage situation.

4.3 Explosive Welding

Developmental work is now being conducted to develop an explosive welding technique suitable for the deep ocean. It is believed that this process may be useful in attaching padeyes to sunken objects to aid in salvage efforts. If development is successful, this device has several advantages which may be exploited for deep application. First little manipulative ability is demanded, in fact, only emplacement and remote detonation are required. Next, the power source for this device is small and self-contained. Finally, the process is simple and inexpensive.

The principle of explosive welding is simple. It has been found that two pieces of metal impacted together at sufficient velocity can form a weld at the interface. An explosive charge provides enough velocity to ensure bonding. Figure 4-9 depicts the basic arrangement required. The upper or flyer plate is projected against the stationary

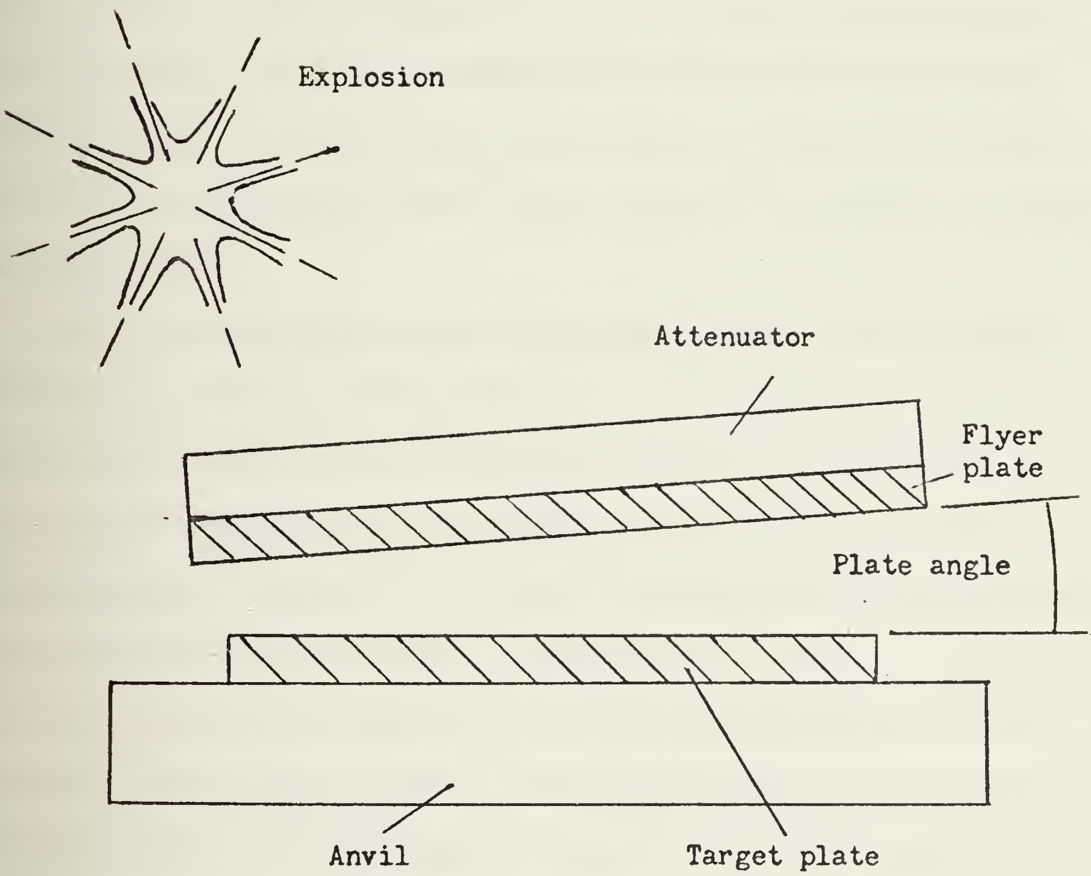


Figure 4-9 Arrangement for Explosive Welding[50]

lower plate or target by the force of an explosion, forming a weld in microseconds with a noticeable lack of overall deformation. There must be a slight angle between flyer plate and target, usually less than five degrees, and the flyer plate may be supported a small distance away from the target. The flyer plate is protected by a rubber or P.V.C. plate, known as an attenuator, which is placed between it and the explosive. A stand-off distance is required for a single explosive charge. Sheet or plastic explosives used for larger area bonding are placed in contact with the attenuator and ignited from the end where clearance between flyer and target is the least. Surface preparation is not critical but deeply pitted, scaly, corroded or roughened surfaces should be avoided.[31]

There is considerable plastic deformation in the immediate region of the faying surface and the hardness of the deformed interface is usually greater than that of the unwelded material. This interface assumes a wavy form with wave amplitudes of from 0.005 to 3/16 inch and wavelengths of from 0.01 to 1/4 inch, depending on welding conditions. Satisfactory welds seem to require the formation of waves. A small jet of metal, known as a surface jet, is often ejected from between the plates as they fold together. The ripples and jet are caused by the high pressures and instantaneous temperatures of the explosive impact, which results in the metal near the bonding front becoming sufficiently plastic to act as a fluid. Under these conditions, the flyer plate acts as a jet traveling across the target plate. Humps are raised in the target region ahead of the jet, then are passed over while new humps form. This causes the rippled or wavy weld interface.

Division of the jet as it strikes the surface results in surface jetting and also in stripping the surface of the contacting plates, exposing metal for bonding.[31]

In the particular technique employed underwater, a second charge, which is timed to detonate a small fraction of a second prior to the main charge, is placed in such a manner as to evacuate the water between the plates. However, as welding depths are increased, progressively larger secondary charges will be needed to evacuate the water since larger pressure forces will be acting to resist evacuation. This presents a real problem since the nearly incompressible water will transmit larger and larger shock waves to the plates as the size of the secondary charge is increased.

In making attachments to highly corroded objects some form of surface preparation must be considered. It is possible that still another charge, properly applied, might achieve this.

One final disadvantage common to both surface and underwater explosive welds should be noted. Welds with good bonding characteristics are difficult to produce consistently. This process appears to be highly sensitive to variations in welding conditions such as the plate separation distance and angle, the explosive standoff distance and the balance between the magnitude of the explosive force and the surrounding environment. Difficult to control precisely in laboratory conditions, these factors may become prohibitive in actual deep sea work.[43]

4.4 Velocity Power Tools

Several velocity power tools have been fully developed for use underwater in salvage and emergency repair work. These devices may be used to attach studs or lifting points, to provide fittings for gas or liquid transfer and to punch holes. Velocity power tools are small, inexpensive, flexible and have a self-contained energy source. Several models have been developed. Of these, two have been designed strictly as diver tools while a third has been designed for remote operation in conjunction with the Navy's LOSS program. These tools can be used on wood, concrete and sheet metal in addition to steel plate.

Each velocity power tool is essentially a gun. As Figure 4-10 illustrates, a stud or other device acts as the projectile. It is attached to a piston which is propelled by the detonation of gunpowder within a standard cartridge. The tool itself uses a trigger and firing pin assembly to detonate the cartridge and propel the piston and projectile down the barrel. Several safety devices are incorporated into each diver operated tool to ensure that premature firing cannot occur. The diver must, before firing, align the barrel assembly in a certain manner and push the barrel against the work with a force of at least five pounds and at an angle of between 82 and 90 degrees.[37]

There are several types of ammunition available for each tool. These include several types of solid studs used for fastening, hollow studs used to transfer a gas or liquid through a bulkhead and a hole punch projectile used to punch a hole through a plate. Each type has a number of powder loads to accommodate plates of various thicknesses.[37]

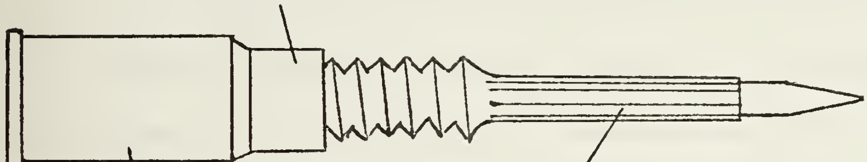


Figure 4-10 Solid Stud Cartridge[37]

The light-duty diver tool operates with a flooded barrel and can be used at depths up to 300 feet. It can be reloaded simply underwater by placing a new projectile-cartridge assembly in the breech. The heavy duty diver tool and the remotely operated tool both operate with sealed barrels in order to accelerate the projectile sufficiently to achieve the required penetration. The heavy duty diver tool can only be reloaded underwater by replacing the entire sealed barrel unit.[37] The present depth capability of sealed barrel units is 1000 feet but it should be possible to extend this limit if the need arises.

Velocity power tools are ideal for attaching temporary patches. One of two methods may be employed. Using the first method, a patch can be essentially nailed to a structure by firing a stud entirely through the patch into the structure. The second method consists of firing studs through predrilled holes in the patch and into the underlying structure. The patch can then be bolted on. Centering plugs on the muzzle of the barrel ensure stud alignment with the hole. Patches and other fittings applied using these tools are capable of withstanding large forces. Average extraction forces for heavy and light weight studs and various plate thicknesses are tabulated in Table 4-2. Loading these studs in shear, rather than tension, increases their load-bearing capacity since pull-out cannot occur. This is done in the Navy's LOSS system.

The primary disadvantage of the velocity power tool is its basically destructive nature. The projectile literally rips its way into the parent structure. Careful matching of powder loads for intended use minimizes the damage, but a stud or other fitting attached in this

Table 4-2[37] Velocity Power Tool Stud Extraction Forces for Structural Steel Plate

Heavy Duty Solid Studs

Plate Thickness	Average Extraction Force
3/8 in.	8,000 lbs.
1/2	14,000
5/8	16,000
3/4	19,000
7/8	22,000
1	26,000
1 1/8	29,000

Light Duty Solid Studs

Plate Thickness	Average Extraction Force
1/4 in.	3,000 lbs.
3/8	3,500
1/2	4,000

manner cannot be considered a permanent part of the structure. Crevices and discontinuities are created which serve as sites for corrosion. This technique is thus limited to salvage and temporary repair. Even in certain salvage situations, the destructive nature of this tool is a disadvantage. If this device were used to provide an attachment point on a watertight compartment of a sunken submarine or submersible, it could cause leakage or even collapse of that compartment. This danger increases as salvage depth is increased.

4.5 Other Processes

There are several processes, other than those outlined above, which are being considered or may in the future be considered for deep ocean use. However, little technical information dealing with the effects of pressure on these techniques is available so only a rather cursory summary will be presented.

4.5.1 Mechanical Joining

Mechanical joining techniques form the heart of several repair systems being developed for the deep sea. These systems, which will be used in the repair of submerged production equipment and pipelines, were discussed in Chapter 2. Mechanical joining methods possess several advantages over other techniques for deep ocean application. First, they are well within the state of the art, requiring little or no developmental effort. Some of these methods are also simple enough to be easily employed by remotely operated manipulator systems. Finally,

these methods are reliable and their results consistent. They can be especially designed for the repair of particular subsea structures.

Mechanical connectors may find their greatest undersea use in the repair of pipelines. Many pipe repair devices have been developed over the years to meet surface requirements for repair techniques in locations where welds could not be made. These devices include mechanical sleeves for bolting and sealing two pipe ends together, split sleeves for the repair of ruptured pipelines, clamps for fixing small leaks and mechanically connected hot tapping saddles. Many present devices rely on multiple bolts and are therefore more compatible with divers than with remotely operated manipulators. However, new connectors which snap together, yet are capable of containing high pressure flow, are being developed.[29]

Mechanical joining devices are also suitable for use in conjunction with other techniques. For example, a sleeve may be mechanically connected and sealed around a pipeline so that flow may be restored. A reinforcing seal weld can then be made between sleeve and pipeline without the danger of explosion which is present when gases cannot be vented from an enclosed space.

4.5.2 Gas Welding

Attempts which have been made to use gas welding processes underwater have met with little success, even though such gases as oxygen-acetylene, propane, methane, ethane, and ethylene have all been tried. Acetylene, in fact, becomes unstable at depths greater than 5 to 10 meters due to increased pressure and can be considered safe

only at pressures less than 10 decibars.[54]

Hydrogen is the only gas which may be useful for deep ocean use since all other fuel gases liquify under ambient pressures at shallow depths. A hydrogen-oxygen combination may prove useful for some applications down to around 1500 meters. Below this depth, even heating units are no longer a feasible means of keeping the hydrogen in a gaseous state and liquification occurs.[54]

4.5.3 Adhesive Bonding

Adhesive bonded joints have been used for many structural applications especially in the aerospace industry.[50] This technique is amenable to remote operation and requires no external power source. In addition, it may be accomplished with little or no external heat curing.[45]

Adhesive bonding occurs primarily as a result of the molecular attraction exerted between the surface to be bonded and the adhesive. Primary chemical and electrostatic forces of attraction form most adhesive bonds, thus suggesting that the strongest bonds are obtainable between highly polar materials. Metal surfaces, although not highly polar by themselves, mirror the forces in a highly polar adhesive placed on them, resulting in a strong bond.[50]

There are a number of adhesives that offer promise for underwater joining. These include butyl rubber-quinoid cure, nitrile rubber-epoxy, polysulfide-epoxy and epoxy-polyamide. Most of these cure at or near 70^{o}F so, in practice, they must either be placed in a heated enclosure or limited to warm water applications. Additional problems

which must be overcome include:

1. Rigorous surface preparation of joints
2. Joint fitup
3. Joint design
4. Methods of introducing adhesive to the joint
5. Curing techniques
6. Strength of joints produced

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS OF SYSTEMS STUDY

5.1 Conclusions

1. Definite requirements exist for extending the operational depth of existing underwater metals joining techniques that are suitable for a wide range of repair tasks. These requirements are most urgent in the offshore petroleum industry and sufficient economic incentive is present in this industry to spur continued development. There is little need at present for construction processes, but such a need may arise in the next decade. Deep ocean devices capable of providing attachment points for remotely operated salvage systems are needed, but only modest developmental efforts are justified by the urgency of this requirement.

2. Present joining processes capable of permanent repair work require a high degree of manipulative ability, which can only be afforded by a skilled welder in direct contact with the workpiece. In order to achieve this, the welder must be subjected to ambient pressure or the work must be enclosed in a one atmosphere chamber. Since the second alternative is practical only in certain extremely limited cases, present repair techniques with the exception of mechanical joining devices, are essentially limited to depths that the human body can withstand. At the present time, these limits are equivalent to from 600 to 1000 feet of water, but tests indicate that these limits may eventually be extended to 2000 feet and deeper.

3 Repair processes which appear most promising for application at greater depths, up to diver limits, include the dry GMA and GTA processes and the wet multipass SMA process.

4. Mechanical joining techniques are versatile and adaptable to remote operation. In the absence of other processes, it is expected that many of these devices will be developed to meet future ocean joining needs at depths beyond diver limits.

5. Devices capable of meeting deep salvage needs can be developed which require little manipulative ability and are thus suitable for employment with submersibles and remote vehicles. Diving systems impose no depth limit on these devices, but power requirements are a major constraint.

6. In spite of limitations, velocity power tools appear to be the most promising joining devices in existance for use in deep ocean salvage operations. Exothermic processes also have advantages which make them attractive potential candidates if fundamental problems can be solved.

7. Welding costs for jobs employing conventional and saturated diving systems increase drastically with depth. Costs for submersible and remote systems increase much more slowly with depth.

8. Cooling effects and hydrostatic forces combine to compress an underwater welding arc, increasing arc penetration.

9. As depth and hydrostatic pressure increase, current density increases and a higher voltage is required to maintain a constant arc length.

10. Increasing the pressure on an electric arc results in a tendency for metal transfer to revert from spray to globular. Increasing the voltage delays the onset of globular transfer, but does not prevent instability and a loss of arc efficiency.

11. The development of new electrode coatings has resulted in extending the depth capacity of the SMA process to over 200 feet for low carbon steels and to 80 feet for steels with high carbon equivalents. Austenitic electrodes have been successfully employed underwater to prevent the onset of hydrogen cracking.

12. Weld metal porosity is reduced in welds made under pressure. This is believed to be due to supression of bubble formation, not to a decrease in the amount of gas in the weld.

13. Pressure increases the rate at which carbon, manganese and silicon deoxidants combine with oxygen.

5.2 Recommendations

1. Efforts should be directed toward identifying and developing processes capable of general repair and construction work, yet suitable for remote operation in depths beyond diver range. At present, there is a decided lack of such processes.

2. No completely satisfactory method of remotely attaching padeyes to sunken objects has yet been developed. New ideas need to be conceived and tested.

3. More attention should be directed toward developing processes capable of the repair of high strength steel structures. In particular, electrode coatings capable of producing high quality SMA multipass welds in high strength steels at depths exceeding 80 feet should be developed.

4. There is a disagreement concerning amperage requirements as a function of depth. Tests to clarify this question should be conducted in waters of sufficient depth to get clear results and care must be taken to ensure that factors such as cable length and diameter do not influence results.

5. The effects of voltage increases on the metal transfer mode of welds made under pressure should receive further study. Lower heat input versions of the GMA process should be investigated as possible solutions to arc instability and deposition efficiency problems.

6. From diffusivity relations and equilibrium diagrams, it appears that hydrogen embrittlement will become a greater problem as welding depths increase. Experimental verification should be conducted.

7. Multipass weld techniques have been used with great success to prevent cracking by tempering welds made underwater. Postheat

treatment has also met with a certain degree of success. More experimental work in this area is recommended.

8. The effects of depth on gas evolution rates should be studied.

9. Methods of removing water from the weld mold and ensuring the flow of metal from the reaction chamber to the mold must be developed to make exothermic welding a practical deep ocean joining process.

CHAPTER 6 CONCEPTUAL DESIGN OF A DEEP OCEAN STUD WELDING SYSTEM

This chapter explores the feasibility of adapting a surface welding process, stud welding, for a particular deep ocean application. This task is approached from a total system viewpoint, with all of the factors outlined in Figure 1-1 considered. In this way, two purposes are served. First, the application of methods and information presented in part one is illustrated. Second, the conceptual design of an integrated system utilizing a proposed deep ocean joining process is presented and the feasibility of this design evaluated.

6.1 Potential Use

There is a recognized need for devices capable of providing attachment points on sunken vessels to aid in salvage or rescue operations and there may soon be a requirement for techniques to make attachments on permanent sea floor structures. These requirements can be met in relatively shallow water using divers and hand-manipulated arc welding techniques. However, no device has yet been developed which completely satisfies the need for a process capable of employment by a submersible or remote vehicle in waters beyond a diver's working depth.

Only one of the processes discussed in Chapter 4, the velocity power stud tool, has completed development and has been produced for operational usage. This device was successfully tested as part of the Navy's LOSS program, but it exhibits certain limitations which may inhibit wider application. Studs attached using this process can be

heavily loaded in shear only and multiple attachments are required for large loads. Discontinuities produced at the joining surface make this technique unsuitable for applications exposed to the corrosive marine environment for prolonged periods. In addition, the impact required to attach large studs may make the use of this device on submarines or other structures containing watertight compartments undesirable.

Studs arc-welded on the surface can be heavily loaded in tension and a single 1 1/4 inch diameter stud weld can withstand a static tensile load of over 60,000 pounds.[66] Smooth weld fillets are produced and the low heat input of this process causes little damage to thick plates.

In brief, needs exist for remote processes to make attachments on undersea structures. The arc stud welding process, if it can be adapted for underwater use, may be able to meet these needs.

6.2 Diving System Considerations

A number of considerations must be included in the choice of a diving system for the deployment of a marine stud welding device. Factors which enter into this decision include depth, cost and support requirements as well as manipulative and maneuverability demands.

The requirement exists for a device for employment in depths well beyond diver range. An acceptable diving vehicle should have a depth capacity of from 1000 to 5000 feet and future requirements may even extend this to 20,000 feet, the depth of the abyssal plain.

Since vehicles employed in deep ocean operations are inherently very expensive, it is essential that this joining system be mated to either an existing ocean vehicle, with modifications, or to a vehicle being designed to perform a variety of tasks.

6.2.1 Support Requirements

A device capable of welding a one inch diameter stud requires direct current electrical power with 2000 amps of current and an open circuit voltage of at least 65 volts.[21] Options available for supplying power to existing deep sea vehicles are essentially limited to surface cables and storage batteries. However, power requirements for studs large enough to be useful in salvage operations effectively preclude storage batteries, due to weight and volume limitations. Any diving vehicle capable of employing a large stud welding device must, then, receive power through a surface umbilical.

Cables capable of transmitting high levels of power, yet of sufficient structural strength and of reasonable size and weight, can be constructed for operations at 20,000 feet. A cable, able to transmit high, short duration loads of sufficient magnitude for arc welding of one inch diameter studs at 20,000 feet, requires a weight of only 2.0 pounds per foot and a diameter of about 1.25 inches.[58]

It is expected that a device which welds in the wet without the need for shielding gases can be constructed. This is dealt with in more detail in the next section. However, as discussed in chapter 3, shielding gas can be carried in small cylinders if it is needed.

Since the actual welding of a stud occurs in a very short span of time, just over a second for a one inch stud, only very small amounts of gas are required for adequate coverage. Argon can be used to 11,700 feet prior to liquification and nitrogen to 16,700 feet, so shielding can be achieved at all but the most severe depths.[54]

6.2.2 Manipulative and Maneuverability Requirements

The operation of a stud welding device requires that the device be placed squarely against the workpiece and held in position while welding takes place. The total time that the device must be held in position is on the order of a few seconds and depends more on the response time of the control system than on welding time. Positioning of the device may be accomplished easily by any one of a number of underwater manipulators now in service. Holding the device in position, however, will require either very fine maneuvering control of the work vehicle or some type of fixture or clamp.

Extensive surface preparation is not required for stud welding but marine growth and corrosion must be removed from the immediate area where the stud is to be attached. This can be accomplished by a rotary wire brush attached to a manipulator. Rotary movement is a very common feature on underwater manipulators.

Reloading a stud welding device in a high pressure environment may be a problem. Many small stud guns used in industry are fed automatically, but none with studs longer than one inch. If a practical loading system cannot be developed, devices with multiple

welding heads may be used.

6.3 Technical Feasibility

The next step in the conceptual design is the investigation of the technical feasibility of the proposal. Stated more simply, it must be determined if the stud welding process can be used directly in a wet environment or if an enclosure and gas shielding system are required. From a total systems viewpoint, assuming both systems can produce satisfactory results, the wet system is to be preferred to the dry since the complications of a gas supply system and an enclosure can be avoided. Eliminating these features makes the overall system simpler, increasing reliability and decreasing cost. It also saves weight and volume, both valuable commodities in any deep sea system.

The approach to the question of technical feasibility is both experimental and analytical in nature. In the experimental portion, welds are made in a wet environment and samples are tested to determine tensile strength, hardness and metallurgical content. In the analytical portion, a computer heat flow model is employed to determine the temperature history of points near the weld. This is done because the large heat sink of the underwater environment changes the metallurgical structure of the weld and these changes can be predicted with a knowledge of temperature history. This model is verified experimentally.

Before proceeding to a more detailed description of experimental and analytical procedures and results, a brief examination of the stud welding process is necessary.

6.3.1 Stud Welding

Stud welding is an automatically controlled arc welding process. Both the stud and the workpiece are heated and melted by an arc which is drawn between them. The two contact points are then brought together rapidly under pressure to form a weld.[66]

The two basic techniques of stud welding are defined by their method of power supply. A motor generator, a transformer rectifier, or a storage battery must be used as a power supply for the first method, arc stud welding. The power supply for the second method, capacitor-discharge stud welding, is a low-voltage electrostatic storage system and the arc is produced by a rapid discharge of stored electrical energy. Both methods involve direct current and arcing and in both cases the stud serves as the electrode and a "stud gun" as the electrode holder.[21]

Stud welding is a rapid process. Depending on the diameter of the stud, welding times vary from 1 to 12 milliseconds for the capacitor-discharge method and from 0.10 to a little more than 1 second for arc stud welding. In arc stud welding, straight polarity is normally used for ferrous alloys and reverse polarity for nonferrous alloys. Straight polarity is used in capacitor-discharge stud welding. Melt-through and distortion are not serious problems in either method. The diameter of the stud weld base should not be more than three times the thickness of the base metal in order to develop maximum strength.[21]

Flux is generally needed for arc stud welding of ferrous alloys to provide a protective atmosphere and cleaning action. When used, flux is placed on or within the stud end during the manufacturing

process. The arc time for the capacitor-discharge method is so short that flux is not needed. In arc stud welding, a porcelain or ceramic ferrule is used at the weld tip to shield and control the welding arc, to concentrate the heat of the arc and to act as a dam to retain the molten weld metal.[66] Arc stud welding results in a much larger weld fillet and heat affected zone than the capacitor-discharge method.[21]

Capacitor-discharge welding can be performed with studs ranging from 1/16 to 3/8 of an inch in diameter. Arc stud welding must be used for diameters greater than 3/8 of an inch and can weld studs of up to 1 1/4 inches in diameter.[21,66] It is expected that large diameter studs, welded using the arc stud process, will be most useful in the deep ocean.

6.3.2 Experimental Procedure

The experimental approach is used to determine if the stud welding process can produce satisfactory welds in a wet environment, without an enclosure or shielding gas system, and to verify the analytical heat flow model. Experiments were conducted in conjunction with Lawrence Zanca.[68]

Equipment and materials used in the experimental procedure are outlined in Table 6-1. The basic experimental setup is shown schematically in Figure 6-1.

In order to obtain samples for tensile and hardness testing and metallurgical examination, the following steps were necessary:

Table 6-1

Experimental Equipment and Materials

1. Omark model DS-G capacitor-discharge stud gun
2. Omark model SS-6 Twin Pack power unit
3. 1008 steel studs with copper flashing
4. 1/4 inch low carbon steel plate (SAE 1018)
5. 27 gage low carbon steel sheet
6. Plexiglass water tank
7. rubber gloves and mat
8. thermometer (mercury in glass)
9. Tempilaq temperature indicating liquid
10. Instron Universal Testing Instrument, Model TTC
11. Wilson Tukon Microhardness Tester, Model LL

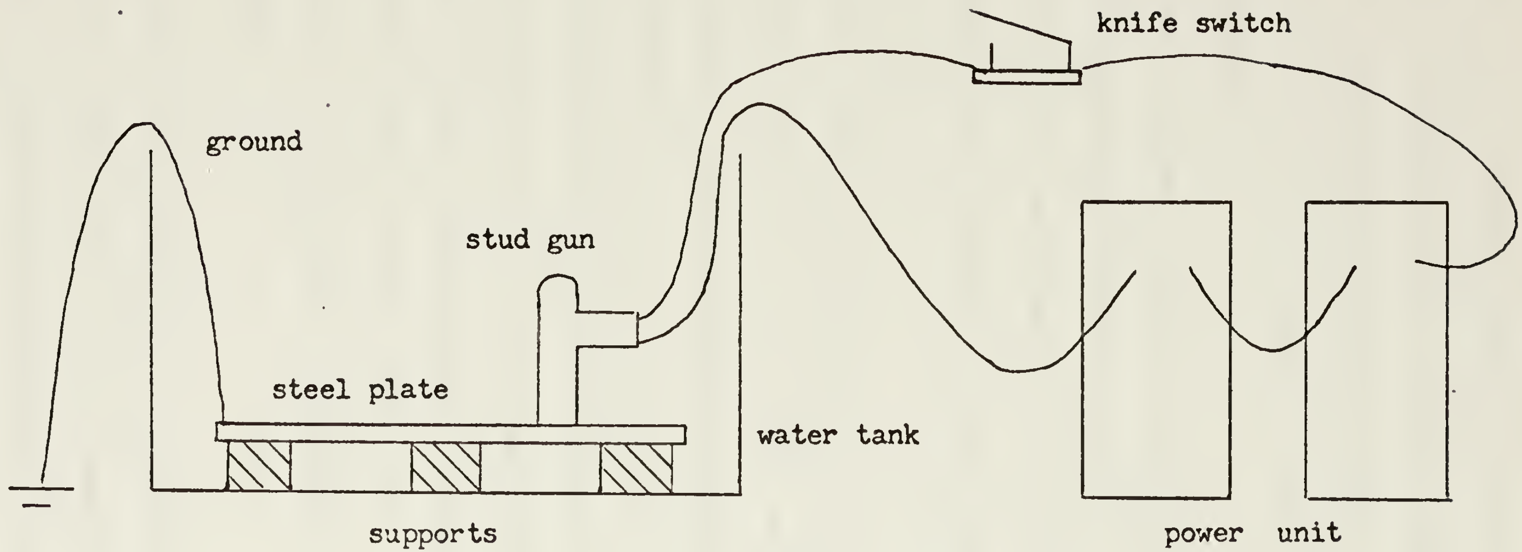


Figure 6-1 Experimental Equipment Schematic

1. The stud gun was waterproofed by sealing the case with a silicon compound and replacing the trigger with a knife switch operated from outside the tank.
2. The 1/4 inch plate was placed on supports in the water tank and grounded.
3. The water tank was filled with water until the plate was four inches below the water surface.
4. Sufficient time was allowed for the plate to attain thermal equilibrium with the water and the temperature of the water was recorded.
5. The power supply unit was set up in accordance with manufacturer's instructions. The power supply to the capacitors was turned on and the capacitors were allowed to charge.
6. An operator, wearing rubber gloves and standing on a rubber mat, placed the stud gun squarely on the plate and, when ready, gave the order to close the switch. An assistant closed the knife switch and the stud was welded onto the plate.
7. The knife switch and power supply were turned off, the gun was removed from the water and reloaded and the process was repeated.

Tensile tests were conducted on an Instron Universal Testing Instrument, using standard stud testing procedures. The maximum load sustained prior to fracture was recorded and it was noted whether failure occurred in the stud or weld.

For hardness testing and metallurgical examination, longitudinal

cross sections of the stud and baseplate were mounted, polished and etched. Hardness testing was performed on a Wilson Tukon Tester using standard procedures and a load of 100 grams. Metallurgical examination was completed using 200 power magnification. Photographs of metallurgical samples were also taken.

In order to obtain data to verify the analytical model the same basic underwater stud welding procedure was utilized with the following exceptions:

1. 27 gage steel squares were used in place of 1/4 inch plate.
2. Before placement in the tank, the back of each square was coated with Tempilaq temperature indicating liquid.

A series of plates was prepared and each plate was coated with Tempilaq of a different melting temperature. Melting temperatures ranged from 250°F. to 800°F. After a stud was welded to each plate, the diameter of the melted portion of Tempilaq was measured to obtain maximum temperature data for various points near the welded stud. It was necessary to obtain measurements from the reverse side of very thin plates because smoke from the welding arc made accurate readings on the front of the plates impossible. Burnthrough presented problems with plates thinner than 27 gage. Each test plate could be exposed to a wet environment for only a short period of time since prolonged exposure caused the temperature indicating coating to peel.

6.3.3 Heat Flow Analysis

The thermal history of a weld made underwater largely determines

the microstructure present in the weld area. Macroscopic properties of the weld such as tensile strength, ductility, hardness, notch toughness and resistance to fatigue are, in turn, directly related to the microstructure. With a knowledge of base metal and stud composition and the temperature history of the weld, microstructure can be predicted to a reasonable degree of accuracy using continuous cooling transformation (CCT) curves.

Anderssen developed a computer heat flow model for studs welded underwater using a thermit process.[5] With modification, his model is applicable to a stud welded underwater using an electric-arc process. Figure 6-2 illustrates the configuration of the model on which the analysis was made. The stud is cylindrical in shape in the area where it contacts the plate.[5]

The general equation of heat flow, in cylindrical coordinates, without source terms and assuming conductivity to be independent of position and T independent of θ is:[44]

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

where: T = temperature change

t = time

r, z, θ = coordinate system

α = thermal diffusivity

The problem is essentially one of heat conduction in the bar and the plate. It is assumed that the stud is insulated from the surrounding

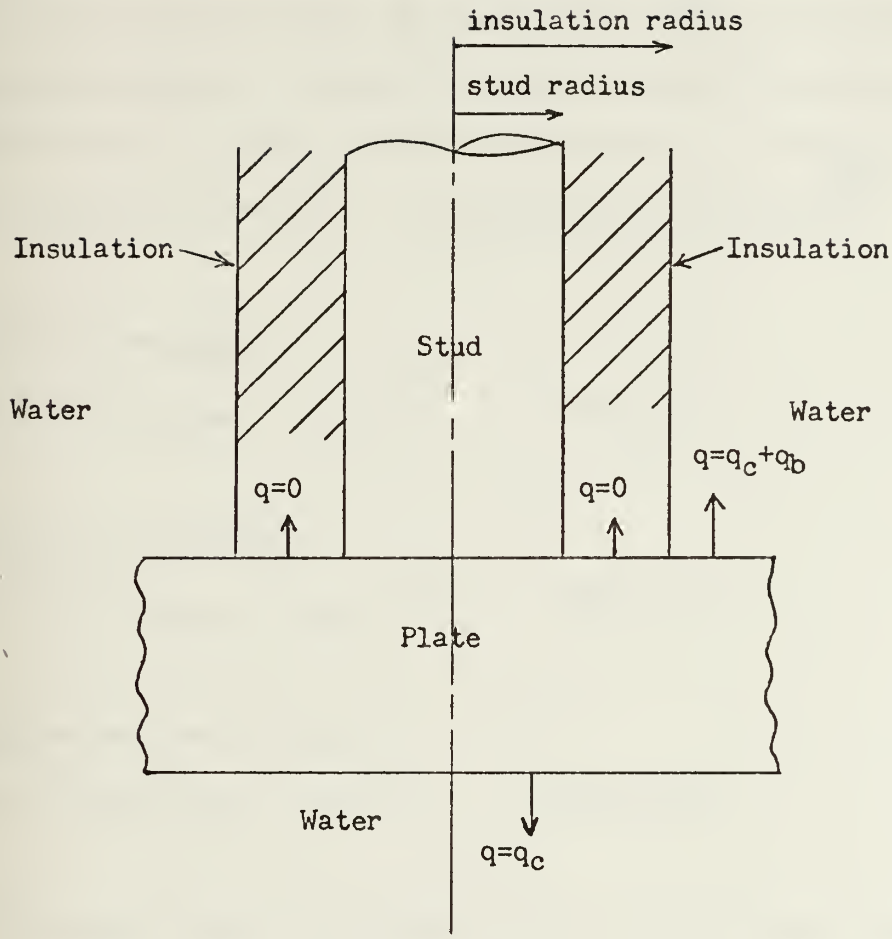


Figure 6-2 Model Configuration for Heat Flow Analysis[44]

water. The ferrule in an arc stud process acts as an insulator but this assumption is inaccurate for a capacitor-discharge weld. The heat loss to the water from the top and the bottom of the plate makes the problem complex. Anderssen's study considered only horizontal plates but even for this restricted case heat loss mechanisms on top and bottom were different. The following values are used:[44]

Top plate convection:

$$q_c/A = 32.2\ (T_{plate} - T_{water})^{4/3} \qquad (\mathrm{BTU/hr/ft^2})$$

Bottom plate convection:

$$q_c/A = 12.2\ (T_{plate} - T_{water})^{5/4} \qquad (\mathrm{BTU/hr/ft^2})$$

Top plate nucleate boiling:

$$q_b/A = 1.7494\ (T_{plate} - T_{sat})^{3} \qquad (\mathrm{BTU/hr/ft^2})$$

Because of restricted bubble activity on the bottom surface, nucleate boiling cannot occur. A semistable vapor film is formed instead which permits transfer only by a radiation mode. However, temperatures of sufficient levels for significant radiation are not expected, so areas of vapor film on the bottom surface are modeled with zero heat loss.[44] In equation form:

Bottom plate nucleate boiling: $q_b/A = 0$

Bottom plate radiation: $q_r/A = 0$

The total heat loss from either surface is the sum of individual components:

$$q/A_{total} = q_c/A + q_b/A + q_r/A$$

Finite-difference computer techniques were used to analyze the unsteady heat conduction problem involving complex losses at plate surfaces. The computer program developed by Anderssen to simulate temperature histories of points in the stud and plate is presented in Appendix B. Instructions for program use, a program listing and a sample input and output are included.

6.3.4 Experimental and Analytical Results

Tensile tests were conducted for air and underwater stud welds made at four different voltage settings. No failures were noted for any of the air welds. At the lowest setting, 125 volts, 50 percent of the wet welds failed. However, at higher settings much better results were obtained. At 140 volts no failures occurred, at 155 volts a 25 percent failure rate was produced and at 170 volts 12.5 percent of the underwater welds failed. Table 6-2 presents complete tensile test results. In interpreting test results, notice must be taken of the fact that sampling size was small and that more wet welds were tested than dry welds.

Figure 6-3 shows a 10 power magnification of a polished and etched, wet stud welded metallurgical sample. From this figure, it is

Table 6-2

Stud Weld Tensile Test Results

Voltage	Condition	No. of Studs Tested	No. of Weld Failures	Failure Percentage
C (125)	Dry	5	0	0
	Wet	8	4	50
D (140)	Dry	4	0	0
	Wet	5	0	0
E (155)	Dry	4	0	0
	Wet	8	2	25
F (170)	Dry	4	0	0
	Wet	8	1	12.5

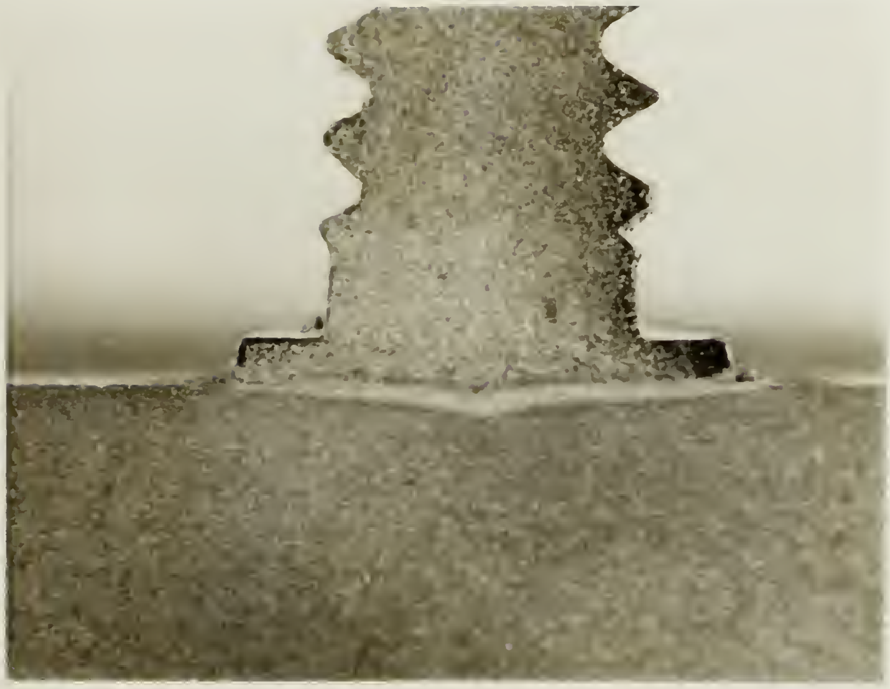


Figure 6-3 Cross Section of Wet Underwater Stud Weld (10 X)

evident that good quality wet stud welds can be made, free of defects such as cracking, porosity, and lack of fusion.

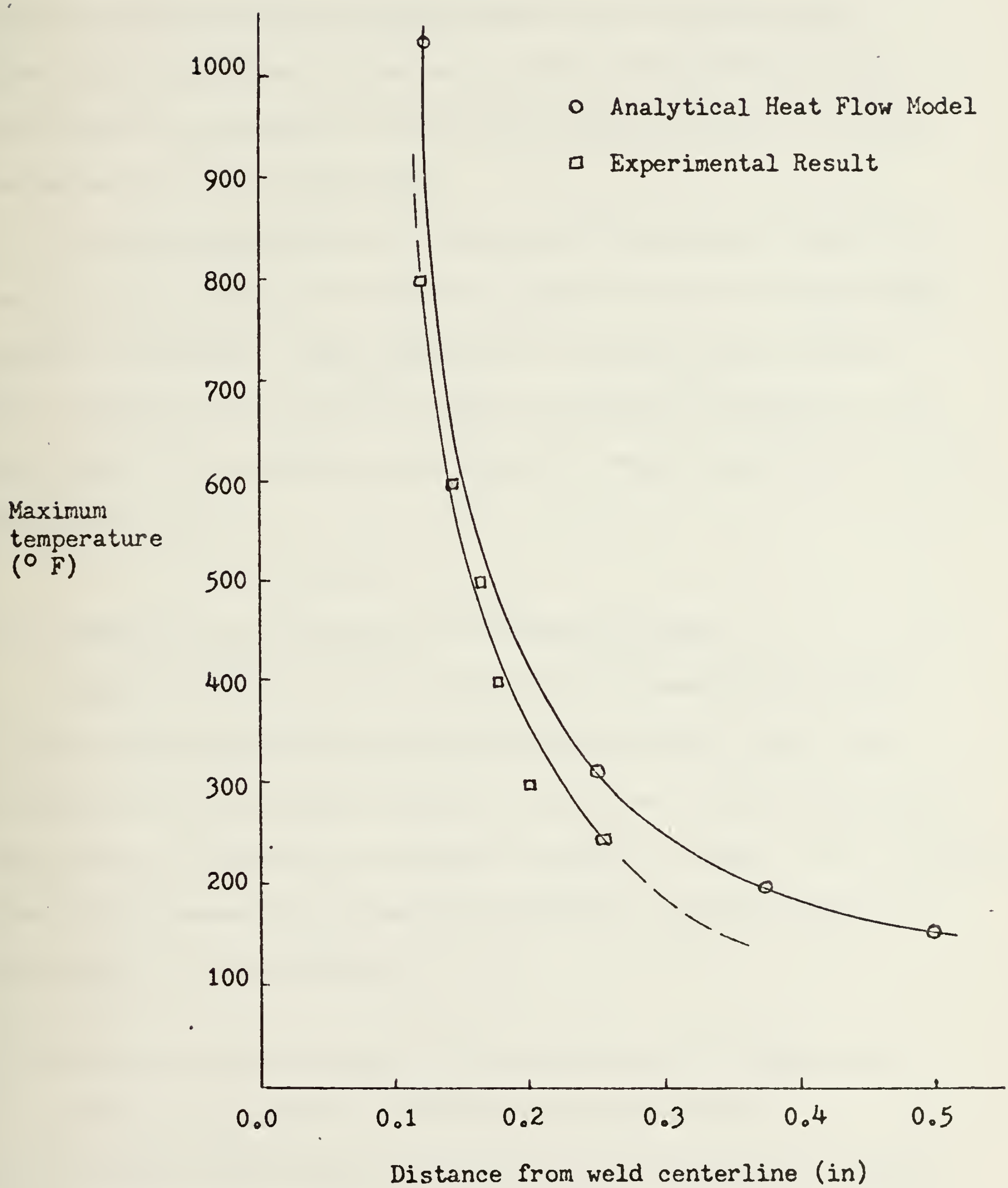
Figure 6-4 illustrates a 200 power magnification of the center portion of the same sample, annoted with hardness values for each of five separate regions. Grain refinement has occurred in the HAZ of both the base metal and stud. In the fusion zone, a relatively large percentage of martensite is present as well as some bainite structure. These structures occur only in those cases where rapid cooling occurs. Both the shallow geometry of a capacitor-discharge stud weld and the underwater environment contribute to rapid cooling. In these experiments, little difference was noted in the microstructure of welds made in air and underwater except that underwater welds tended to have slightly smaller weld zones. This leads to the conclusion that rapid cooling can be attributed largely to the geometry of the stud weld.

Verification of the computer heat flow model is completed using maximum temperature data for points in the plate, rather than temperature histories for these points. This is done because the small size of the studs welded in these experiments (base diameter, 0.25 in.) precluded the installation of thermocouples.

Figure 6-5 presents the maximum temperature attained at various distances from the stud centerline. Results predicted by the analytical heat flow model as well as results obtained from experimental efforts are included. This figure suggests that a reasonably close correlation between theoretical predictions and experimental results exists. Insulation assumptions included in the analytical heat flow model shift

Figure 6-4 Cross Section of Wet Underwater Stud Weld (200 X)

Figure 6-5 Heat Flow Model Verification



that curve to the right, compared to experimental results which are derived from a non-insulated capacitor-discharge stud weld.

Figure 6-6 presents the cooling rate curve for the center of the stud weld superimposed on the CCT diagram for low-carbon steel. From this illustration, it can be seen that the relatively large quantities of martensite and the bainite found in Figure 6-4 can be predicted by the heat flow model.

In summary these results indicate that satisfactory stud welds can be made in a wet environment and that no enclosure or gas supply system is necessary. These results also indicate that a computer heat flow model can be used to predict temperature histories in the weld areas. This knowledge can be used to predict microstructure and weld properties.

6.4 Formulation and Evaluation of Conceptual Design

Previous sections of this chapter may be summarized to yield a set of desirable attributes for the overall system. This list constitutes the conceptual design of a deep ocean stud welding system and serves as a model for evaluating the entire concept. The conceptual design also becomes the guideline for detailed equipment design if the project is deemed feasible.

1. The work vehicle employed in this system must be capable of a wide range of missions in addition to stud welding.
2. The total system should eventually be able to operate in depths of at least 5000 feet.

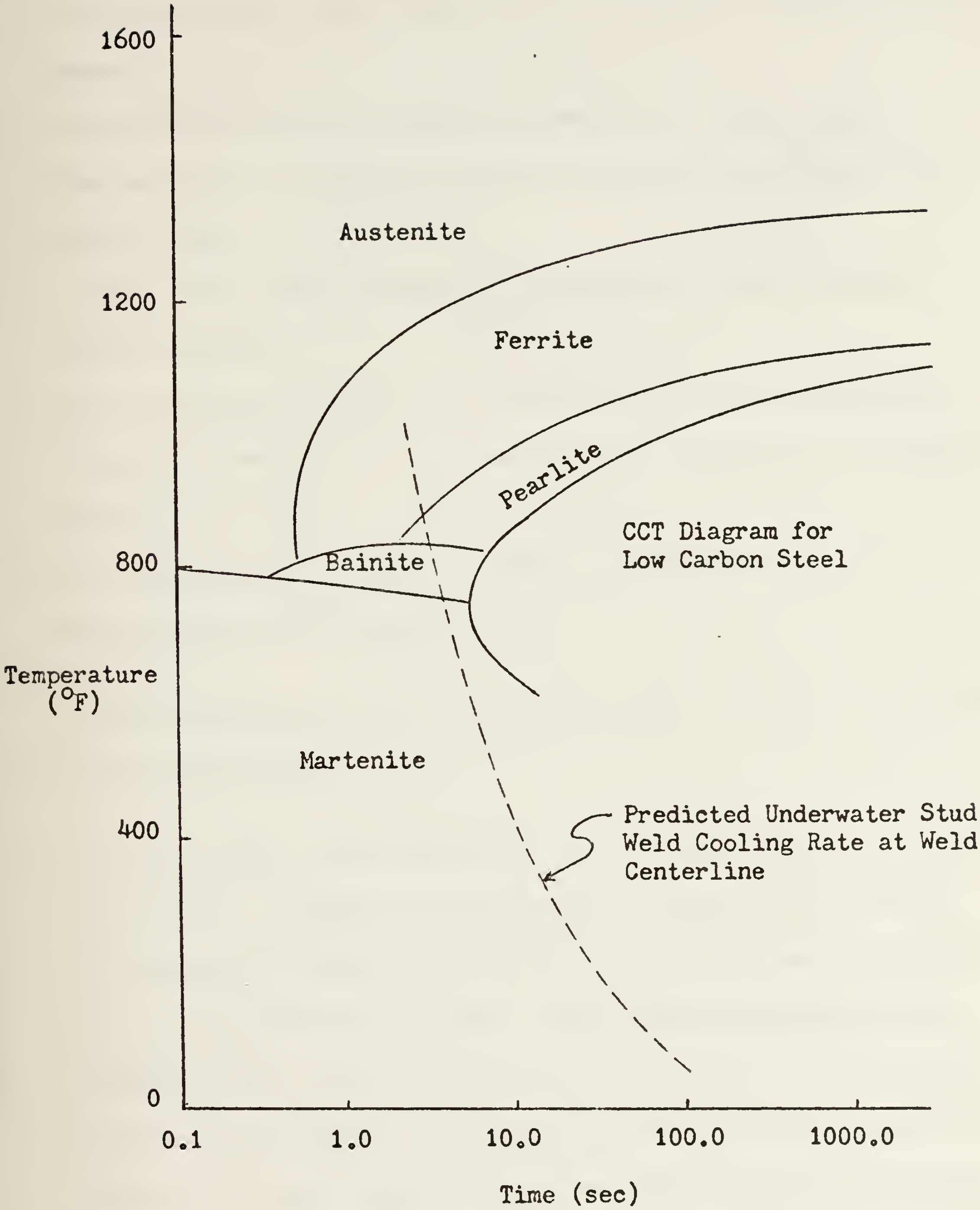


Figure 6-6 Predicted Stud Weld Cooling Rate

3. Safety and cost considerations favor an unmanned, remotely operated system.
4. A surface-connected cable must be used for the power source.
5. The capacity to rough-clean the weld area prior to welding must be provided.
6. Stable welding head placement for a period of 5 to 10 seconds must be assured.
7. The arc-welding process can be carried out in a wet environment without the complication of a welding head enclosure or gas supply system.
8. The stud welding gun must be capable of automatic reloading or must employ multiple welding heads.

In the evaluation of this conceptual design, two major limitations are of prime importance:

1. It is not known if an electric arc can be used at depths as great as 5000 feet. Studies of the effects of pressure on a welding arc have been confined to relatively modest pressures, equivalent to several hundred feet at most. High pressure studies must be undertaken before stud welding can be considered a viable candidate for deep ocean application. Since most of the salvage work anticipated in the near future will involve ferrous metals, development of flux tips for studs used in a high pressure, wet environment is another area requiring research. Work done for SMA electrodes may be applicable to the arc stud process.

2. The requirement for a surface supplied power source places the stud welding process at a disadvantage when it is compared with the self-contained devices examined in Chapter 4. This essentially restricts this process to use with surface-tethered diving systems only. In particular, it prevents its use with most manned submersibles. Whether this is an important restriction or not depends upon the demands the overall salvage operation places on the work vehicle.

On the positive side, most of the diving requirements imposed in the conceptual design can be met by existing remotely operated recovery vehicles, such as the U.S. Navy's CURV III, with only relatively minor modification. Existing surface stud welding guns also appear to be relatively easy to adapt to underwater use.

In summary, the stud welding process requires an extensive developmental effort before it can become operational. Even then, it will be somewhat limited by the large pulse of electrical power it demands. The advantages that stud welding offers over the existing velocity power tool are, at present, not sufficient to justify the costs involved in developing the stud welding process for deep underwater use.

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APPENDIX A

CALCULATION OF COST VS DEPTH RELATIONS FOR DIVING SYSTEMS

Welding Costs for Conventional Surface Diving

depth	bottom hrs. / man day	Daily Costs: salary [a]	depth bonus [b]	support [c]	DDC [d]	HeO_2 [e]	cost / bottom hr.
33 ft.	7 hr.	$ 2000	---	$1500	---	---	$ 125
50	4	2000	---	1500	$ 75	---	223
70	3.5	2000	$ 20	1500	75	---	261
100	2.43	2000	50	1500	75	---	388
140	1.9	2000	130	1500	150	---	549
170	1.2	2000	210	1500	150	---	935
210	0.33	2000	340	1500	150	$2090	5,340

All costs apply to a team of 4 welder/divers and include contractor overhead where applicable.

Charges based on Gulf of Mexico rates.

(a) 500 $/day/welder

(b) Variable with depth

(c) Includes diving and welding support equipment (Diving barge additional if required)

(d) Decompression Chamber (DDC) required below 50 ft. depth

(e) HeO_2 breathing mixture required below 200 ft.

Welding Costs for Saturation Diving

Total Job Costs

job duration	depth	time under pressure[a]	salary[b]	sat syst and support[c]	mixed gas[d]	mobilization	cost / bottom hr.[e]
1 day	200 ft.	3 days	$ 14,400	$ 45,000	$ 12,000	$ 16,000	$ 3,642
1	500	6	28,800	90,000	18,000	16,000	6,367
2	200	4	19,200	60,000	20,000	16,000	2,400
2	500	7	33,600	105,000	26,000	16,000	3,763
5	200	7	33,600	105,000	44,000	16,000	1,655
5	500	10	48,000	150,000	50,000	16,000	2,200
5	800	13	62,400	195,000	56,000	16,000	2,745
10	200	12	57,600	180,000	84,000	16,000	1,407
10	500	15	72,000	225,000	90,000	16,000	1,679
10	800	18	86,400	270,000	96,000	16,000	1,964

See footnotes next page

Welding Costs for Saturation Diving (footnotes)

All costs apply to a team of 4 welder/divers and include contractor overhead where applicable. Charges based on Gulf of Mexico rates.

(a) One day decompression required for each 100 feet of depth regardless of job duration

(b) 1200 $/day under pressure/diver

(c) 15,000 $/day includes saturation diving system and diving and welding support equipment (Diving barge additional if required)

(d) Mixed gas cost assumed 8,000 $/day for work, 2,000 $/day in chamber (Gas cost actually increases with depth but cost data unavailable)

(e) 6 working hours/bottom day/diver

Manned Submersible Deployment Costs[24]

depth	$\frac{\text{bottom hrs.}}{\text{day}}$	$\frac{\text{cost}}{\text{bottom hr.}}$
1 ft.	10 hr.	$ 1,280
500	10	1,299
1,000	10	1,318
5,000	8	1,765
10,000	6	2,450
15,000	4	3,635
20,000	2	6,821

All costs apply to a manned, untethered submersible with an operating endurance of 12 hours.

Coat data: (1) Surface support 12,000 $/day

(2) Salary and consumables 80 $/hour

(3) Capital recovery factor is 37.05×10^{-3} $/hour/ft.

(Reference 24 adjusted for 8% annual inflation)

Remotely Operated Work Vehicle Deployment Costs[24]

depth	bottom hr. / day	cost / bottom hr.
1 ft.	24 hr	$ 535
500	24	554
1,000	24	573
5,000	24	728
10,000	24	921
15,000	24	1,114
20,000	24	1,307

All costs apply to an unmanned, tethered remotely operated work vehicle with an operating endurance of several days.

Cost data: (1) Surface support 12,000 $/day

(2) Salary and consumables 35 $/hr.

(3) Capital recovery factor is 38.61×10^{-3} $/hour/ft.

(Reference 24 adjusted for 8% annual inflation)

APPENDIX B

INSTRUCTIONS FOR PROGRAM USE

PROGRAM LISTING

SAMPLE DATA DECK

SAMPLE OUTPUT

INSTRUCTIONS FOR PROGRAM USE

The temperature simulation program has been written in FORTRAN language and can be executed without difficulty on any computer having a FORTRAN Compiler and 153,600 bytes of primary storage for use by the program. The user is required to furnish the following information describing the material, the environment, the device configuration, and the points for which temperature histories are desired.

Three items of input data, THERM, EFF, and FLOW have been altered from Anderssen's original program in order to describe the characteristics of an arc welding process rather than a thermit process.

1. First data card (FORMAT (4F10.4)):

   TENV: temperature of the water where the weld is to be made. (°F)

   TSAT: water saturation temperature at the depth the weld is to be made. (°F)

   TSOL: solidification temperature of the metal. (°F)

   THERM: arc temperature. (°F)

2. Second data card (FORMAT (5F10.4))

   GAP: distance between the bar and the plate. (in)

   RBAR: radius of the bar. (in)

   RINS: radius of the insulation. (in)

   THICK: plate thickness. (in)

   EFF: arc efficiency.

3. Third data card (FORMAT (2F10.4))

   RHO: density of metal at fusion temperature. (lbm/in^3)

   QFUS: latent heat of fusion of metal. (Btu/lbm)

4. Fourth data card (FORMAT (I3))

   IVAL: the number of data cards immediately following which describe thermal properties of the plate and bar. (maximum of 100)

5. Fifth group of data cards (FORMAT (3F10.5))

   TPROP: temperature at which particular property holds. (^oR)

   CON: thermal conductivity at temperature.(Btu/ft-hr-^oR)

   DIF: thermal diffusivity at temperature. (ft/hr)

6. Next data card (actual number depends upon the number of cards describing properties) (FORMAT (2F10.4))

   TSIM: desired simulation time. (sec)

   FLOW: arc duration (sec)

7. Next to last data card (FORMAT (12I5))

   Cylindrical coordinates of six points in the plate for which temperature histories are desired in the number of eighths of an inch a point is away from the center of the weld and plate top.

8. Last data card (FORMAT (4I5))

   Coordinates of four points in the bar or weld material for which temperature histories are desired in the number of eighths of an inch a point is away from the top of the plate.

```
C                PROGRAM FOR PREDICTING TEMPERATURE DISTRIBUTIONS OF BAR TO
C                PLATE WELD UNDERWATER
C
C
      REAL M
      DIMENSION T(21,100),TP(21,100),U(100),UP(100),R(100),BETA(10),
     2ETA(10),TPROP(100),CON(100),DIF(100)
      READ(5,1006) TENV,TSAT,TSOL,THERM
 1006 FORMAT (4F10.4)
      READ(5,1007) GAP,REAR,RINS,THICK,EFF
 1007 FORMAT (5F10.4)
      READ(5,1008) RHO,QFUS
 1008 FORMAT (2F10.4)
      READ(5,1004) IVAL
 1004 FORMAT (I3)
      READ(5,1005) (TPROP(IPROP),CON(IPROP),DIF(IPROP),IPROP=1,IVAL)
 1005 FORMAT (3F10.5)
      READ(5,1009) TSIM,FLOW
 1009 FORMAT (2F10.4)
      READ(5,1010) IIA,JA,IIB,JB,IIC,JC,IID,JD,IIE,JE,IIF,JF
 1010 FORMAT (12I5)
      READ(5,1011) IG,IH,IJ,IK
 1011 FORMAT (4I5)
      WRITE (6,1000)
      WRITE (6,1001)
C
      PI=3.14159
      S=0.125
C                UNITS: IN
      DELT=0.1
C                UNITS: SEC
      EVAC=FLOW*0.5
C                UNITS: SEC
      LEVAC=IFIX(EVAC/DELT)
      LFLOW=IFIX(FLOW/DELT)
      THERM=THERM*EFF
```

```
      THERI=THERM-140.0
      QFUS=-QFUS
      DO 25 IZ=1,10
      BETA(IZ)=999.9
      ETA(IZ)=0.0
   25 CONTINUE
      TEND=TSIM/DELT
      LTEND=IFIX(TEND)
      ITOP=100
      ITOPM=99
      IIBOT=IFIX(THICK/S)+1
      JMAX=49
      JMAXP=50
      JBAR=IFIX(RBAR/S)+1
      JBARM=JBAR-1
      JINS=IFIX(RINS/S)+1
      LPR=IFIX(1.0/DELT)
      R(1)=0.0
      DO 10  J=2,JMAXP
      R(J)=R(J-1)+S
   10 CONTINUE
      DO 20  I=1,ITOP
      U(I)=TENV
      UP(I)=TENV
   20 CONTINUE
      DO 30  II=1,IIBOT
      DO 30  J=1,JMAXP
      T(II,J)=TENV
      TP(II,J)=TENV
   30 CONTINUE
      IGAP=ITOP-IFIX(GAP/S)
      DO 40  I=IGAP,ITOPM
      U(I)=THERM
   40 CONTINUE
      IIA=IIA+1
      JA=JA+1
```

```
      IIB=IIB+1
      JB=JB+1
      IIC=IIC+1
      JC=JC+1
      IID=IID+1
      JD=JD+1
      IIE=IIE+1
      JE=JE+1
      IIF=IIF+1
      JF=JF+1
      IG=100-IG
      IH=100-IH
      IJ=100-IJ
      IK=100-IK
C
C              START TIME LOOP
C
      DO 700 L=1,LTEND
C
C              BAR TEMP CALCULATION FOLLOWS
C
      DO 100 I=50,ITOPM
      IY=I-IGAP+1
  901 UPROP=(U(I-1)+U(I+1)+U(I))/3.0+460.0
      IPROP=IFIX(UPROP/50.0)+1
      IF(IPROP.GT.IVAL) IPROP=IVAL
      DIFUS=DIF(IPROP)/25.0
      CONDU=CON(IPROP)/43200.0
      M=S**2/(DIFUS*DELT)
      UP(I)=(U(I-1)+U(I+1))/M+(1.0-2.0/M)*U(I)
      IF(I.LT.IGAP) GO TO 100
  902 IF(L.GT.LEVAC) GO TO 991
      DO 98 IX=IGAP,ITOPM
      UP(IX)=THERI
   98 CONTINUE
      GO TO 100
```

```
  991 IF(L.GT.LFLOW) GO TO 997
      DO 99 IW=IGAP,ITOPM
      UP(IW)=THERM
   99 CONTINUE
      GO TO 100
C
C              START SOLIDIFICATION ROUTINE
C
  997 IF(U(I).GE.TSOL.AND.UP(I).LE.TSOL) GO TO 992
      GO TO 100
  992 IF(BETA(IY).EQ.999.9) GO TO 996
      IF(BETA(IY).LT.(1.0-ETA(IY))) GO TO 994
      GO TO 995
  996 UP(I)=TSOL
      ETA(IY)=(U(I-1)+U(I+1)-2.0*U(I)-M*(TSOL-U(I)))*CONDU*DELT
     2/(RHO*QFUS*S**2)
      IF(ETA(IY).LT.1.0) GO TO 993
      IF(ETA(IY).EQ.1.0) GO TO 100
  995 UP(I)=(U(I-1)+U(I+1)-(RHO*QFUS*S**2)/CONDU)/M+(1.0-2.0/M)*U(I)
      ETA(IY)=0.0
      GO TO 100
  994 ETA(IY)=ETA(IY)+BETA(IY)
  993 BETA(IY)=(U(I-1)+U(I+1)-2.0*U(I))*DELT*CONDU/(RHO*QFUS*S**2)
  100 CONTINUE
C
C              END BAR TEMPERATURE CALCULATION
C
      DO 200 II=1,IIBOT
      DO 200  J=1,JMAX
      IF(II.EQ.1.AND.J.LE.JBAR) GO TO 90
      GO TO 80
C
C              AVE TEMP AND 1D INTO AVE CALCULATION FOLLOWS
C
   90 AREA=PI*(S/2.0)**2
      TAVE=T(2,1)*AREA
```

```
      DO 300 K=2,JBARM
      AREA=AREA+2.0*PI*R(K)*S
      TAVE=TAVE+T(2,K)*2.0*PI*R(K)*S
  300 CONTINUE
      AREAR=PI*(R(K)-S/4.0)*S
      TAVE=TAVE+T(2,JBAR)*AREAR
      AREA=AREA+AREAR
      TAVE=TAVE/AREA
      UPROP=(U(ITOPM)+TAVE+T(II,J))/3.0+460.0
      IPROP=IFIX(UPROP/50.0)+1
      IF(IPROP.GT.IVAL) IPROP=IVAL
      DIFUS=DIF(IPROP)/25.0
      M=S**2/(DIFUS*DELT)
      TP(II,J)=(U(ITOPM)+TAVE)/M+(1.0-2.0/M)*T(II,J)
      UP(ITOP)=TP(1,1)
      GO TO 200
C
C              2D CALCULATION FOLLOWS
C
   80 IF(II.GT.1) GO TO 70
C
C              2D ON TOP BORDER FOLLOWS
C
      IF(J.GT.JINS) GO TO 81
      QTOTL=0.0
      GO TO 82
   81 QCONV=-.0000681*ABS(T(II,J)-TENV)**1.33333
      QBOIL=0.0
      IF(T(II,J).LE.TSAT) GO TO 811
      QBOIL=-.0000034*ABS(T(II,J)-TSAT)**3.0
  811 QTOTL=QBOIL+QCONV
   82 UPROP=(T(II+1,J)*R(J)+T(II,J-1)*R(J-1)+T(II,J+1)*R(J+1)+T(II,J)
     2*R(J))/(2.0*R(J)+R(J-1)+R(J+1))+460.0
      IPROP=IFIX(UPROP/50.0)+1
      IF(IPROP.GT.IVAL) IPROP=IVAL
      DIFUS=DIF(IPROP)/25.0
```

```
      CONDU=CON(IPROP)/43200.0
      M=S**2/(DIFUS*DELT)
      TP(II,J)=(2.0*T(II+1,J)+T(II,J-1)*(1.0-S/(2.0*R(J)))+T(II,J+1)
     2*(1.0+S/(2.0*R(J)))+(QTOTL/CONDU)*2.0*S)/M+(1.0-4.0/M)*T(II,J)
      GO TO 200
C
C                2D INTERIOR FOLLOWS
C
   70 IF(II.EQ.IIBOT) GO TO 60
      IF(J.EQ.1) GO TO 71
      UPROP=(T(II-1,J)*R(J)+T(II+1,J)*R(J)+T(II,J-1)*R(J-1)+T(II,J+1)
     2*R(J+1)+T(II,J)*R(J))/(3.0*R(J)+R(J-1)+R(J+1))+460.0
      IPROP=IFIX(UPROP/50.0)+1
      IF(IPROP.GT.IVAL) IPROP=IVAL
      DIFUS=DIF(IPROP)/25.0
      M=S**2/(DIFUS*DELT)
      TP(II,J)=(T(II-1,J)+T(II+1,J)+T(II,J-1)*(1.0-S/(2.0*R(J)))
     2+T(II,J+1)*(1.0+S/(2.0*R(J))))/M+(1.0-4.0/M)*T(II,J)
      GO TO 200
   71 UPROP=(T(II-1,J)*S+T(II+1,J)*S+T(II,J+1)*8.0*R(J+1)+T(II,J)*S)
     2/(3.0*S+8.0*R(J+1))+460.0
      IPROP=IFIX(UPROP/50.0)+1
      IF(IPROP.GT.IVAL) IPROP=IVAL
      DIFUS=DIF(IPROP)/25.0
      M=S**2/(DIFUS*DELT)
      TP(II,J)=(T(II-1,J)+T(II+1,J)+4.0*T(II,J+1))/M+(1.0-6.0/M)*T(II,J)
      GO TO 200
C
C                2D ON BOTTOM BORDER FOLLOWS
C
   60 QCONV=-.0000235*ABS(T(II,J)-TENV)**1.25
      QTOTL=QCONV
      IF(J.EQ.1) GO TO 61
      UPROP=(T(II-1,J)*R(J)+T(II,J-1)*R(J-1)+T(II,J+1)*R(J+1)+T(II,J)
     2*R(J))/(2.0*R(J)+R(J-1)+R(J+1))+460.0
      IPROP=IFIX(UPROP/50.0)+1
```

```
      IF(IPROP.GT.IVAL)  IPROP=IVAL
      DIFUS=DIF(IPROP)/25.0
      CONDU=CON(IPROP)/43200.0
      M=S**2/(DIFUS*DELT)
      TP(II,J)=(2.0*T(II-1,J)+T(II,J-1)*(1.0-S/(2.0*R(J)))+T(II,J+1)
     2*(1.0+S/(2.0*R(J)))+(QTOTL/CONDU)*2.0*S)/M+(1.0-4.0/M)*T(II,J)
      GO TO 200
   61 UPROP=(T(II-1,J)*S+T(II,J+1)*8.0*R(J+1)+T(II,J)*S)/(2.0*S
     2+8.0*R(J+1))+460.0
      IPROP=IFIX(UPROP/50.0)+1
      IF(IPROP.GT.IVAL)  IPROP=IVAL
      DIFUS=DIF(IPROP)/25.0
      CONDU=CON(IPROP)/43200.0
      M=S**2/(DIFUS*DELT)
      TP(II,J)=(T(II-1,J)+4.0*T(II,J+1)+(QTOTL/CONDU)*S)/M+(1.0-5.0/M)
     2*T(II,J)
  200 CONTINUE
C
C              END PLATE CALCULATION
C
      DO 500  I=2,ITOP
      U(I)=UP(I)
  500 CONTINUE
      DO 600  II=1,IIBOT
      DO 600  J=1,JMAX
      T(II,J)=TP(II,J)
  600 CONTINUE
C
C              THE FOLLOWING CAUSES TEMP FOR SELECTED POINTS TO BE
C              WRITTEN EVERY SECOND
C
      IF(FLOAT(L/LPR).EQ.FLOAT(L)/FLOAT(LPR)) GO TO 50
      GO TO 700
   50 TEMPA=TP(IIA,JA)
      TEMPB=TP(IIB,JB)
      TEMPC=TP(IIC,JC)
```

```
      TEMPD=TP(IID,JD)
      TEMPE=TP(IIE,JE)
      TEMPF=TP(IIF,JF)
      TEMPG=UP(IG)
      TEMPH=UP(IH)
      TEMPJ=UP(IJ)
      TEMPK=UP(IK)
      LPRX=L/LPR
      WRITE (6,1003) TEMPA, TEMPB, TEMPC, TEMPD, TEMPE, TEMPF, TEMPG,
     2TEMPH, TEMPJ, TEMPK, LPRX
  700 CONTINUE
C
C                 END TIME LOOP
C
 1000 FORMAT ('1',T20,'TEMPERATURE HISTORIES OF SELECTED POINTS')
 1001 FORMAT ('0',14X,'A',8X,'B',9X,'C',8X,'D',8X,'E',8X,'F',9X,'G',8X,
     2       'H',8X,'J',8X,'K',9X,'SEC')
 1003 FORMAT (10X,10F9.0,I10)
      STOP
      END
```

```
C      SAMPLE DATA DECK
C
C
C
60.0         212.0       2740.0     4000.0
 0.20        0.125       0.13       0.25       1.0
    0.2835 1213.88
 70
  50.        45.5        2.31225
 100.        44.5        2.05584
 150.        43.5        1.57996
 200.        42.5        1.39509
 250.        41.8        1.12003
 300.        41.0        1.04429
 350         40.0        0.99457
 400.        39.2        0.89311
 450.        38.5        0.82756
 500.        37.6        0.76845
 550.        36.8        0.73780
 600.        36.1        0.70351
 650.        35.2        0.65597
 700.        34.5        0.60482
 750.        33.8        0.58294
 800.        32.8        0.56199
 850.        32.0        0.54489
 900.        31.2        0.52739
 950.        30.5        0.50348
1000.        29.7        0.47212
1050.        29.0        0.44432
1100.        28.2        0.41701
1150.        27.5        0.40462
1200.        26.8        0.39177
1250.        25.9        0.35928
1300.        25.0        0.33571
1350.        24.5        0.31919
1400.        23.3        0.29566
```

1450.	23.1	0.27598
1500.	22.2	0.24465
1550.	21.8	0.22843
1600.	21.1	0.20136
1650.	20.6	0.14922
1700.	20.0	0.14046
1750.	19.5	0.12877
1800.	19.0	0.13384
1850.	18.8	0.1528
1900.	18.1	0.18214
1950.	17.8	0.23510
2000.	17.2	0.22717
2050.	17.0	0.22453
2100.	16.5	0.21793
2150.	16.1	0.21264
2200.	15.9	0.21000
2250.	15.5	0.20533
2300.	15.2	0.20165
2350.	15.0	0.19935
2400.	14.9	0.19855
2450.	14.5	0.19379
2500.	14.1	0.18895
2550.	14.0	0.18400
2600.	13.7	0.18050
2650.	13.4	0.17700
2700.	13.2	0.17350
2750.	12.9	0.17000
2800	12.6	0.16600
2850	12.4	0.16300
2900.	12.1	0.15900
2950.	11.8	0.15550
3000.	11.5	0.15200
3050.	11.3	0.14800
3100.	11.0	0.14500
3150.	10.7	0.14100
3200.	10.5	0.13800

```
3250.      10.2      0.13400
3300.       9.9      0.131
3350.       9.7      0.12700
3400.       9.4       .12400
3450.       9.1      0.12000
3500.       8.9      0.11600
 30.0      0.01
    0    0   0    1    0    2    0    3    0    4    0    5
    1    2   3    4
```

SAMPLE OUTPUT TEMPERATURE HISTORIES OF SELECTED POINTS

A	B	C	D	E	F	G	H	J	K	SEC
812.	812.	223.	98.	68.	62.	2333.	808.	352.	159.	1
1037.	1037.	280.	148.	95.	73.	1689.	1047.	595.	329.	2
1023.	1023.	292.	176.	117.	89.	1380.	1075.	723.	459.	3
924.	924.	310.	184.	134.	102.	1152.	1025.	771.	539.	4
806.	806.	289.	198.	144.	112.	979.	940.	771.	583.	5
699.	699.	276.	199.	151.	119.	848.	851.	745.	599.	6
615.	615.	265.	197.	154.	124.	743.	770.	706.	596.	7
546.	546.	254.	195.	156.	127.	660.	696.	662.	582.	8
492.	492.	248.	193.	156.	129.	593.	635.	620.	562.	9
448.	448.	243.	191.	155.	130.	538.	583.	580.	539.	10
412.	412.	239.	187.	153.	129.	492.	537.	542.	514.	11
381.	381.	234.	182.	151.	129.	454.	498.	508.	490.	12
356.	356.	227.	178.	149.	128.	422.	463.	477.	466.	13
334.	334.	218.	173.	146.	127.	394.	433.	450.	444.	14
315.	315.	210.	168.	143.	125.	370.	407.	425.	423.	15
298.	298.	201.	163.	140.	123.	349.	384.	403.	405.	16
282.	282.	194.	158.	137.	122.	330.	364.	383.	387.	17
269.	269.	186.	154.	134.	120.	313.	346.	365.	371.	18
257.	257.	180.	150.	131.	118.	299.	330.	349.	356.	19
245.	245.	174.	145.	128.	116.	285.	315.	334.	343.	20
235.	235.	168.	142.	126.	114.	273.	302.	321.	330.	21
226.	226.	163.	138.	123.	112.	262.	289.	308.	318.	22
218.	218.	158.	135.	120.	110.	251.	278.	297.	307.	23
210.	210.	153.	131.	118.	108.	242.	268.	286.	297.	24
203.	203.	149.	128.	116.	107.	233.	258.	276.	287.	25
196.	196.	145.	126.	114.	105.	225.	249.	267.	278.	26
190.	190.	142.	123.	112.	103.	218.	241.	259.	270.	27
184.	184.	138.	120.	110.	102.	211.	234.	251.	262.	28
179.	179.	135.	118.	108.	101.	205.	226.	243.	255.	29
174.	174.	132.	116.	106.	99.	199.	220.	236.	248.	30

Thesis
M748 Moore
Metals joining in
the deep ocean.

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